DEGREE PROJECT IN ENERGY AND ENVIRONMENT,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2019

Aalto University
School of Engineering

Carbon dioxide emissions modelling in a power system model:

A case study of Germany and Poland

MARCELINA CHOLI

KTH ROYAL INSTITUTE OF TECHNOLOGY SCHOOL OF ENGINEERING SCIENCES

Aalto University in Espoo, Finland
KTH Royal Institute of Technology in Stockholm, Sweden

MASTER’S THESIS

Carbon dioxide emissions modelling in a power system model:
A case study of Germany and Poland.

Author: Marcelina Choli

Supervisor at KTH: Georgios Avgerinopoulos
Supervisor at Aalto: Mika Järvinen
Supervisor at Fortum: Jussi Mäkelä

Examiner at KTH: Francesco Fuso Nerini
Examiner at Aalto: Martti Larmi

A thesis submitted in fulfilment of the requirements for the Double Master’s Degree in the Innovative Sustainable Energy Engineering (ISEE), track Energy Systems as a part of the Joint Nordic Master’s Programme.

June, 2019

Aalto University
School of Engineering

Aalto University, P.O. BOX 11000, 00076
AALTO
www.aalto.fi

Abstract of master's thesis

Author: Marcelina Choli

Title of thesis: Carbon dioxide emissions modelling in a power system model: A case study of Germany and Poland.

Master programme: Joint Nordic Master's Programme in the Innovative Sustainable Energy Engineering, track Energy Systems **Code:** MJ248X

Thesis supervisor: Mika Järvinen

Thesis advisor(s): Georgios Avgerinopoulos; Jussi Mäkelä

Date: 25.06.2019 **Number of pages:** 73 **Language:** English

Abstract

This study aims to build a method for validating a power system model in the PLEXOS software. Special emphasis is put on the carbon dioxide emissions modelling. A case study of Germany and Poland is formulated in order to apply the created procedure to a European power model. The verification of emissions being one of the outputs, is divided into two phases. The first one focuses on the historical results from 2016-2017, which are compared with the chosen reference statistics and the emissions results obtained in another optimization tool. The second phase looks into the trends of emissions in the near future, i.e. time period between 2019-2025. OSeMOSYS as the second piece of software is used for benchmarking the results obtained by the PLEXOS model.

Keywords: PLEXOS, OSeMOSYS, power system model, carbon dioxide emissions, German power system, Polish power system.

Acknowledgments

The completion of this thesis would not be possible without the support from my supervisors, family and friends. I would like to especially thank to my parents Anna and Jarosław, sisters Justyna and Magda for bearing my ups and downs and listening to me every day patiently. They have found out a lot about the principles of working of the power sector and have been the best 'crossing-fingers' team. They always give me a motivation to push my limits up and help me to accomplish the set goals.

I am very grateful to Jussi Mäkelä who has been my thesis supervisor and manager during the internship at Fortum. He believed in me and gave me an opportunity to grow as a professional and learn from the experienced energy analysts every day. He was always able to give me a constructive feedback and create a great atmosphere within our team. A big 'thank you' to all of the OMI and Industrial Intelligence teams based in Espoo and Stockholm for answering my questions, giving advices and being just amazing colleagues. Working at Fortum was definitely one of these life experiences I am going to appreciate and recall with a smile.

It is impossible to express with words how happy I was to have Georgios Avgerinopoulos as my thesis supervisor at KTH. He is not only an outstanding energy system expert with an extensive knowledge, amazing work ethics and management skills. I find him also as my good friend who always knows what to say to cheer me up or give an advice. Thank you, George! See you in Warsaw/London.

And last but not least – my friends! Thank you Jusia for being my best friend despite of a huge distance between us and seeing each other three times per year. It is an unspeakable feeling to know that you can rely on someone and tell about your daily successes and problems twenty-four-hour. Rebeca, you know the struggles we had to go through while writing our theses. Thank you for lending me your computer so I could run the OSeMOSYS models and the most important - thank you for being such a huge support and my friend. I am so happy that we could work together at Fortum and create such a good duet! Sabrinitao – thank you for these 2 years spent together studying, being travel buddies, sharing an apartment, cooking, hanging out and supporting in all of the life aspects. Only two girls enrolled in the ISEE Energy Systems 2017-2019 – we rock!

-Marcelina

List of Content

List of Figures

List of Tables

List of Abbreviations

BAU – Business As Usual

CCS - Carbon Capture and Storage

CDM - Clean Development Mechanism

CHP – Combined Heat and Power (known also as: Cogeneration)

CO_2 – Carbon Dioxide

EEA - European Environment Agency

ELMOD-DE – An open-source Spatial Optimization Model of the Electricity Sector for Germany

ENTSO-E - European Network of Transmission System Operators for Electricity

EPS - Energy Policy Simulator

ERU - Emission Reduction Unit

ESD – Effort Sharing Decisions

ETS – Emissions Trading System

ETSAP - Energy Technology System Analysis Program

EU – European Union

EUA – European Emissions Allowances

EUTL - European Union Transaction Log

EV – Electric Vehicles

GDP - Gross Domestic Product

GHG – Greenhouse Gases

IEA - International Energy Agency

JI – Joint Implementation

LCP - Large Combustion Plants

LDC – Load Duration Curve

LP – Linear Programming

LT – Long Term Plan

MSR – Market Stability Reserve

MoManI – Model Management Infrastructure

MT – Medium Term Schedule

N_2O - Nitrous Oxide

OSeMOSYS – Open Source Energy Modelling System

PASA - Projected Assessment of System Adequacy

PEP2040 - Energy Policy by 2040 in Poland

PFC – Perfluorocarbon

PP – Power plant

PSE - Polish Transmission System Operator

RE – Renewable Energy

ST – Short Term Schedule

1. Introduction

1.1. Background

Climate change is a global threat. Europe is estimated to be responsible for 10% of the greenhouse gases (GHG) generated worldwide. The latter cause an increase in the global temperature. The Paris Agreement (United Nations, 2015), signed by 181 parties, aims to maintain this temperature rise below 2°C with a possibility to reach even more ambitious target, i.e. to limit the rise at the level of 1.5°C compared to pre-industrial period. Significant changes are expected to take place in the energy sector since it contributes in 75% (excluding maritime and aviation sectors) to GHG generation (European Commission, 2018a). The right policies should be implemented to provide a sustainable development of the energy sector and to achieve the objectives that have been set.

Apart from energy efficiency improvements, leading to lower final energy consumption, greater penetration of renewables is expected. This is one of the ways for a sustainable energy system transition to materialise in line with doubling the size of the economy by 2050 compared to 1990 (European Commission, 2018a). Energy models help to quantify the projected changes in the long-term vision by considering many factors and processes like energy generation, social aspects or economic drivers representing the energy market behaviour. They give more insights into the complexity of the process and indicate the possible solutions (Pfenninger et al., 2014).

Carbon dioxide (CO_2) accounts for the greatest share in GHG, generated primary in the energy sector by fossil fuel combustion (IEA, 2017). Its reduction is fundamental in terms of climate change mitigation. The European Union (EU) set up the world's first international Emission Trading System (EU ETS) in 2005 (European Commission, 2016a). It works in accordance with the principle *cap and trade* to limit pollutants by distributing the emission allowances (EUA). One permit allows to emit one tonne of CO_2 (or equivalent). High CO_2 prices should be an indirect incentive to invest more in carbon-neutral technologies. At the same time, the EU ETS as an emission volume-control system is expected to better fulfil reduction targets than the fiscal tools. Especially in terms of industries, this solution is seen as the most flexible and the cheapest one, according to the *Climate Targets* report (DEHSt, 2013). The system covers, among others, power and heat sector, energy-intensive industries and commercial aviation (European Commission, 2016a). This in turns brings closer to another long-term goal, i.e. achieving net zero GHG emissions by 2050 in Europe. Countries belonging to the emission system, set their own targets and present the roadmaps, whereas the EU oversees only the overall performance (European Commission, 2018a).

1.2. Research Question and Objectives

The study aims to answer the following research question: '*How to set the PLEXOS European power system model up correctly in terms of the generated CO_2 emissions and how to validate the results?*'

The main objective of this study is to create a method allowing to validate the PLEXOS European power sector model developed for the Fortum company's use and shared for the purposes of this master thesis. A special emphasis is put on the levels of CO_2 emissions generated by the model as one of the outputs. Considering the example of Germany and Poland as a case study, a method aiming to validate and improve the model's result is created. Achieving this goal is assumed to be possible by providing two profound analyses of the historical values of emissions for the years 2016-2017, as well as the future ones between 2019-2025, generated by the model.

1.3. Scope and Limitations

The pilot countries, i.e. Germany and Poland, are chosen as the case study since they are considered to be the biggest CO_2 emitters in Europe (European Commission, 2019). The problem of identifying and understanding the statistics used for the model's results validation, constitutes a challenging and interesting case to build a thesis statement on.

A developed methodology enabling the model validation and proper assessment of the model's result, is expected to be a base for the model developers to improve the whole model including more European countries within a set time horizon. At the same time, a proper set-up of the PLEXOS model is investigated in order to obtain the reliable results of CO_2 emissions.

In addition, narrowing the scope is caused by the limited timeframe for the study as well as a possibility to focus more on the state of the energy sector in the chosen countries.

The results are influenced by a few factors, among others:

- Data scarcity resulting in making assumptions;
- No distinction between heat and power sectors in most of the statistics;
- No distinction between unit's type and purpose within the EU ETS activities;
- Covering only power sector in the PLEXOS model in comparison with the aforementioned complexity of the EU ETS as a whole;
- Significant size of the model resulting in long time needed to complete simulations;
- Inconsistent input to the model from the various sources and requiring the manual adjustments.

1.4. Literature Review

This chapter is a comparison of different models aiming to predict the possible levels of generated CO_2 emissions on a country or European level and used in the studies that are relevant to the current report. This is also an introduction to the intricacy of the CO_2 emissions modelling problems, and it aims to acquire the necessary knowledge.

A trial to catch the vulnerability to changes of the energy sector, in line with a need to create long-term strategies, was a starting point for the energy system models. The complexity of problems faced by the energy industry and plethora of factors affecting its transition, have resulted in focusing on linear programming (LP) methods. The first model of this kind was launched in 1976 by International Energy Agency (IEA) as a part of the Energy Technology System Analysis Program (ETSAP). It was followed by founding the research centres and further developments (Pfenninger et al., 2014).

The optimization models constitute an important tool for the analysts enabling to understand the energy systems, predict their behavior and an impact of taken actions. Some of the software become open for the users, i.e. the access is free of charge and quite often provides a basic dataset. The *Energy Policy Simulator* (EPS) developed by the Energy Innovation LLC (Energy Innovation LLC, 2019) is one of them. The model can be used online via the main website or can be downloaded with the complete data input for, among others, Poland. The main goal of the EPS is to indicate the best policy steering towards climate change mitigation. The model's output returns the emissions of twelve different pollutants, a cost related to the implementation of new technologies, the energy consumption with its generation coverage, a profile of the vehicle fleet or the externalities, e.g. human deaths caused by worsened air quality.

An example of the open source model built for Germany is the Spatial Optimization Model of the Electricity Sector *ELMOD-DE* (D. I. W., 2007). The model embraces the electricity sector and includes the generation portfolio with an inclusion of the physical transmission network on a nodal level. ELMOD's principle, as most of the optimization models, is to minimize the total cost of the analysed problem. Moreover, each model is implemented in a specified modelling language, in the case of ELMOD it is *GAMS*, what is tied to an LP solver, e.g. *CPLEX* which is found to be a commercial solution.

By analyzing the energy sector, an economic aspect of the new investments, like building new thermal power plants or implementing renewables, must be also taken into account. This linkage is possible to obtain by using the *hybrid models* (Pfenninger et al., 2014). They usually are a combination of the bottom-up models (presented above) with the top-down general economic models. As a result, the hybrid models bring insights into economy response on the energy system changes. Long-term scenarios of the technological changes in the energy sector in Germany together with their impact on gross domestic product (GDP), were studied by using the *REMIND-D* model (Schmid et al., 2012). As a result, the social welfare was maximized by investing in cost-efficient solutions and taking into account price of fuels, CO_2 reduction or development of low-carbon technologies.
A hybrid energy-economy model for Poland was created by the Polish AGH university academics, by coupling TIMES-PL and TIMES-MACRO models (Suwała et al., 2017). This helped to estimate the CO_2 abatement and its implications while considering different EUA prices and climate regulations.

However, the GHG emissions or energy system transition targets can be also set on a European level. In that case, the European power sector models, aggregating the energy systems of all of the EU Member States, are useful. The exchange balances and international connections can be checked and optimized, while the results are available both for the whole system, as well as separately for each country. The *REEEM* project (REEEM, 2019), sketches the pathways towards the low-carbon economy. Twelve optimization models focusing on different aspects are integrated into one modelling framework allowing to expand the complexity of the project. Moreover, the set of indicators assessing the actors outside of the modelling software, are defined.

1.5. Collaboration

The study was developed in association with *Fortum Sverige AB* in Stockholm, as well as with the head quarter *Fortum Oyj* located in Espoo. The content support, access to the PLEXOS software, workshops and professional collaboration were provided by Fortum staff. The OSeMOSYS models used for the purpose of this study, were developed at KTH Royal Institute of Technology in Stockholm.

2. Methodology

The PLEXOS power sector model validation, being the main goal of the thesis is divided into two phases:

- *PAST Phase*: comparing the PLEXOS historical results with the chosen statistics available online between 2016-2017, as well as with the values returned by the OSeMOSYS models;
- *FUTURE Phase*: comparing the trends of future levels of generated CO_2 emissions by 2025 obtained as a result of two modelling software, PLEXOS and OSeMOSYS.

Figure 1 below shows the structure of the analysed sources and their comparison to each other. The chosen statistics and used models are be described in the following sections.

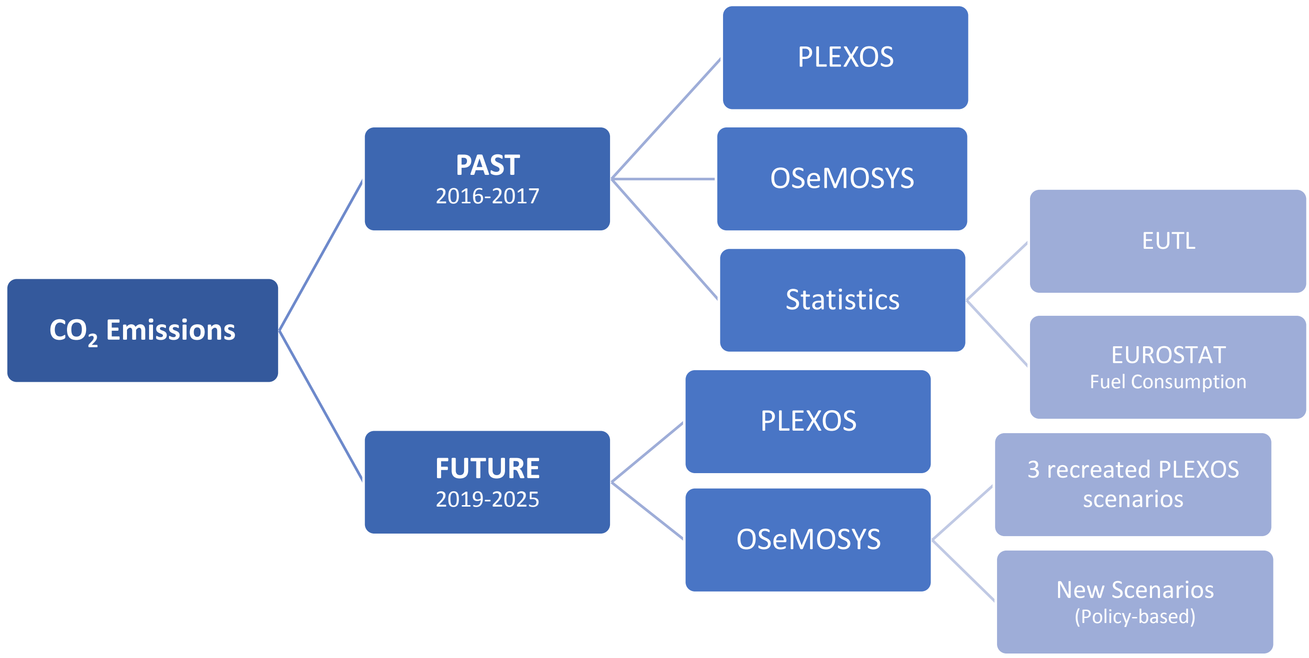


Figure 1: Structure of the analysed sources and their comparison to each other.

Validation of the historical values, i.e. real values of CO_2 emissions obtained in the analysed period in the past, should be done by checking the corresponding values gathered in the official and reliable reference statistics. For the purpose of this thesis, the Union Registry (European Commission, 2016b), collecting the facilities emitting air pollution and participating in the EU ETS, is used. The verified levels of emissions assigned to the registered units, are available in the European Union Transaction Log (EUTL), (EUTL, 2017).

The comparison of assumptions, model's behaviour in the future or trends of the results, might be done by performing a simulation with the aligned input in other modelling tools. In this study, the models for Germany and Poland built in OSeMOSYS software are chosen. They were created as a part of the European project REEEM and further adopted during the *MJ2383 HT18-1 Energy System Economics, Modelling and Indicators for Sustainable Energy Development* course at KTH. The models are only further adjusted and changed for the purpose of this study. Prepared scenarios together with chosen energy policies for the targeted countries, help to estimate the future trends of CO_2 emissions level and its possible abatement. In this way, the countries' contribution towards climate change mitigation is checked.

This chapter introduces the fundamental principles of used software with a special focus on the CO_2 modelling. A detailed description of a basic PLEXOS model, i.e. containing an initial phase where the input is provided, as well as the simulation phase within required settings, can be found in Appendix B. The presented modelling frameworks gather only the basic information about the used model.

2.1. PLEXOS Overview

2.1.1. Fundamental Principles

PLEXOS Simulation Software is an Energy Exemplar product (Energy Exemplar, 2019), which is constantly improved since 1999 due to the rising customers' needs. It is an optimization-based simulation tool for multi-dimensional problems related to the energy sector. PLEXOS can capture the complexity of the issues occurring simultaneously, like long planning connected with the system reliability. The software is mainly used in:

- Energy system modelling;
- Electricity and water optimization;
- Electricity and gas optimization;
- Implementation and integration of renewables to the system;
- Market analysis with a focus on price forecasting, risk assessment, policies evaluation, scenarios creation, market transition;
- Transmission planning;
- Trading support;
- New investments planning and budgeting (Energy Exemplar, 2019).

2.1.2. Framework of the Used Model

A variety of options and a possibility to model complex problems enable to define the same problem in a few ways. Chosen procedures different from the standard settings, are pointed out to show the possibilities of PLEXOS and to bring some insight in terms of its alternative usage.

The basic PLEXOS model containing the main objects is described in Appendix B. The power plants are modelled as *generators*. Some of them are implemented and considered individually, whereas others are aggregated in the bigger groups, which is a good practice in the case of many units with smaller capacities but higher importance from the market's point of view.

Germany and Poland are considered as the *Regions* as a part of the continental model. They constitute a coherent part of the model set-up. By changing the parameters in one country, the others are also affected. This illustrates the complexity of the model and explains the narrowing scope down to the methodology creation and model validation. Reasonable effects can be achieved only by adjusting all of the components at the same elaborated level simultaneously.

Another deviation from the basic set-up is the scenarios' formulation. In the tested model the scenarios are a coherent part where different settings are defined. It means that even by running the basic model, all of the scenarios must be included. This helps to organise a volatile input and implement the changes in a fast and efficient way. Instead of changing the individual parameters manually, a new scenario, e.g. the new capacities of the coal-fired power plants gathered in one Excel file, can be easily implemented.

2.1.3. CO_2 Emissions Set-up

The analysed emissions can be associated with the *Generators* and/or *Fuels* objects. In the used model they are linked only to the *Fuel* objects by defining the *Production Rate* property. The latter indicates the rate of released emissions as a function of fuel consumption and is expressed in [kg/MWh] (*kg* of emission per *MWh* of generated electricity).

Figure 2 presents a structure of the *Emissions* object and its memberships in the PLEXOS model. In the *Production* tab, there are two properties, *Price* and *Shadow Price*. However, only *Shadow Price* is defined what considers it for both emission dispatch and emission accounting. Its value changes frequently and thus, it must be constantly updated. As an input, the *Shadow Price* is the incremental cost of the released Emissions.

The constraint *Max Production Year* sets a cap on emissions generated every year. It is not used for the analysed countries since the EU sets one common goal of emissions reduction for all of the Member States (European Commission, 2018a).

The property *Removal Rate* available for the *Emission.Generators* collection (note the notation with a dot for the *collections*) is valid only for the new introduced installations with the *Carbon Capture and Storage* (CCS) technology whose usage is optimized in PLEXOS. This property indicates the rate of emissions which are first produced and then removed/scrubbed by the assigned generator. For instance, the *Removal Rate* can be the same for all of the new units, equal to 92% what stands for releasing the remaining 8% of emissions out of each installation.

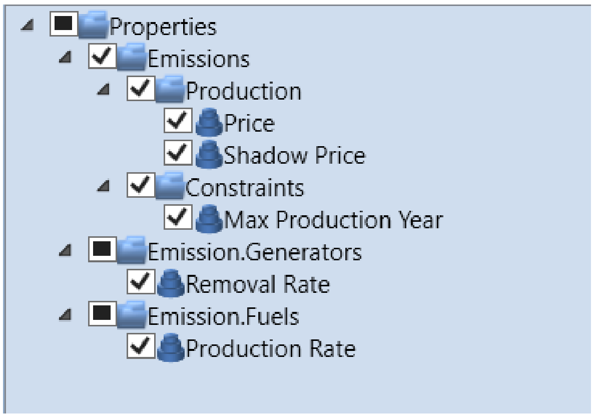


Figure 2: Structure of the Emissions object with its memberships and properties in PLEXOS.

An example of calculating the amount of CO_2 emissions [kg] by generating 1 [MWh] of power:

CCGT1 Generator: 1 Unit

Generator Heat Rate (Fuel efficiency): 7.9 [GJ/MWh]

Generator Max Capacity: 320 [MW]

CO_2 Production Rate for Natural Gas Fuel: 68.4 [kg/GJ]

CO_2 Emissions = 68.4 * 7.9 = 540 [kg/MWh]

2.1.4. Analysed Model Set-ups

Running different scenarios, i.e. testing possible courses of events depending on the implemented set of parameters, is a good practice to identify the most important objects which have got an impact on CO_2 modelling. Forecasting is based on the official information affecting the future, e.g. known decommissioning of coal-based power plants, but is not free of assumptions.

For the purpose of this thesis, three different model set-ups of the PLEXOS models built for Germany and Poland, are tested:

1. ***'Base Case'*** constitutes an updated version of the original model. The reference database of the power plants is the EUTL, where the emitting units are registered. Thus, the model set-

up contains a revised and adjusted set of the condensing power plants to match the one reported to the Union Registry. The missing units from the list are implemented to the model. Moreover, the installed capacities and operation dates announced at the official websites of power plants, are amended. The model set-up considers also the limited operation of some of the Polish units caused, e.g. by insufficiently prepared grid, what is implemented as a reduced installed capacity. This procedure enables to reflect the real operation of the Polish thermal stack.

2. ***'New Emission Factors'*** comprises all of the assumptions and changes applied to the *'Base Case'* model set-up. Additionally, it is upgraded with the new values of CO_2 emission factors to match the official ones applied to all of the Member States (Koffi et al., 2017). The unified EU emission factors are used for the emissions calculation within the EU ETS. Additionally, the national emission factors for lignite in Germany (Jurich, 2016), and Poland (KOBIZE, 2016), are provided. The latter takes into account the fuel quality burnt in a country since the calorific value of a fuel is directly translated into the magnitude of generated emissions.
3. ***'EUTL stack'*** is again an elevated version of the *'New Emission Factors'* model set-up. Some of the stationary installations from the modelling set-up are disactivated since according to the EUTL they are not the condensing power plants but CHP units. Their capacities are moved to the CHP objects in the model to provide the same degree of installed capacity per fuel in a country. As a result, this model set-up constitutes the most reliable reflection of the dataset found in the EUTL. All of the condensing power plants reported to the Union Registry, both in Germany and Poland, have the installed capacities exceeding 50 MW, even though the EUTL is a database for the stationary installations bigger than 20 MW. Two exact lists of the condensing power plants reported to the EUTL in Germany and Poland, and thereby modelled in this model set-up, are available in Appendix C.

2.2. OSeMOSYS Overview

2.2.1. Fundamental Principles

OSeMOSYS (Open Source Energy Modelling System) is an optimization model for the long-term energy planning (KTH-dESA, 2018a). The software enables to analyze a broad-size range of energy systems (continents to villages). Multiple stakeholders have been using OSeMOSYS (e.g. academics, policymakers, etc.), and the system is characterized by no upfront investment since it does not use any proprietary infrastructure (i.e. code, solver or interface). The main principle of OSeMOSYS is to minimize the total discounted cost for the whole modelling period and to cover the specified demand by finding the most suitable energy supply mix (including capacity expansion). The model input contains the set of parameters required to define chosen technologies, relative costs and constraints, which can be modified according to the underway policies and predicted trends.

MoManI (Model Management Infrastructure) is an interface and the browser-based tool which allows to operate OSeMOSYS by data manipulation, designing scenarios and results visualization. It provides the possibility of a parallel work on the same model, what is a convenient solution for the group projects (KTH-dESA, 2018b).

2.2.2. Framework of the Used Model

The adopted models of the power sector for Germany and Poland present the Business As Usual (BAU) scenarios with a timeframe 2015-2060. The projections of future developments in the system constitute a continuation of the historical trends, thus they depict a situation when no action of the energy system development is taken. Some minor changes to the BAU scenarios are implemented in order to align, among others, the capacities and emission factors, with the corresponding values in the PLEXOS models. What is more, the wrong assumptions, i.e. too fast implementation of first nuclear power plant in Poland or too slow coal-phase out in Germany, are identified and ruled out. All of the assumptions and changes to the OSeMOSYS models are described in Appendix C.

BAU constitutes a good reference case enabling a comparison with the alternative, new scenarios created for this study. It helps to visualize the impact of implemented energy policies or technological adjustments on the multiple outcomes, e.g. a country's energy mix, share of renewables, CO_2 emissions, etc. The new scenarios are based on the energy policies whose main assumptions are described in Appendix A.

2.2.3. CO_2 Emissions Set-up

OSeMOSYS allows the users to model chosen types of emissions from each technology on the annual or model period level. A set of constraints ensures that the model does not return the values exceeding the stipulated limits. There is also a possibility to calculate the total associated emission penalty endured if the emissions are higher than it is appointed in the dispensed allowances (KTH-dESA, 2018c).

Defined emissions (CO_2, NOx, etc), are assigned only to the main emitting technologies. The parameter *EmissionActivityRatio* [Mt/PJ] is a counterpart of the *Production Rate* parameter in PLEXOS. The emission factors set the emission level (expressed in Mt) per quantity of fuel needed to obtain one unit of energy (PJ – units of activity in MoManI). The parameter *AnnualEmissionLimit* sets a cap on the emissions generated by a defined region (e.g. country) on annual level.

Apart from the basic settings described above, there is a possibility to consider the emissions calculated outside of the model, e.g. derived from the transport sector, by defining the parameter *AnnualExogenousEmissions*. The penalties endured by exceeding the emissions cap can be modelled by using the *EmissionPenalty* parameter [USD/t_{CO2}].

2.2.4. Analysed Model Set-ups

In this section, the most important changes to the existing models are presented. A detailed list of implemented modifications, assumptions and recalculations of the units is attached in Appendix C.

Despite of the fact that the study focuses on the period by 2025, the implemented changes are applied to the whole available modelling timeframe, i.e. by 2060. It is followed by creating the graphs and analysing the results only for the chosen years. This procedure contributes to the better quality of results since the solutions, e.g. installing new capacities, are cheaper when spread over time.

The same model set-ups analysed in the PLEXOS software, were recreated in OSeMOSYS, i.e.:

1. ***'Base Case'*** containing the same installed capacities per fuel, fixed and variable costs, demand, carbon price and constraints for the new investments (maximum built capacity), as it is set in the corresponding model set-up in PLEXOS.

2. ***'New Emission Factors'*** being a development of the *'Base Case'* model set-up and containing the exact emission factors used in the 2nd analysed model set-up in PLEXOS. A table with the recalculated emission factors for both of the models can be found in Appendix C.
3. ***'EUTL stack'*** including the changes provided in the above model set-up, as well as the adjusted capacity per technology to match the one provided in the corresponding model set-up in PLEXOS. Thus, the capacity of CHP units is increased and the one of condensing power plants (technologies grouped by fuel) is accordingly decreased.

All of the above model set-ups in OSeMOSYS are aligned to the previously completed ones in the PLEXOS models to provide the highest level of input accuracy. Due to the fact that the condensing power plants in PLEXOS are modelled individually, some of the properties, e.g. variable operation and maintenance costs defined individually for each power plant, are aggregated for the groups of power plants fired with the same fuel, and an average value is calculated. The OSeMOSYS model contains only a set of different technologies with a fuel distinction, thus applying the average values is the only reliable way providing the models' alignment.

Another simplification is the annual dimension of the parameters, whereas PLEXOS requires a dataset on an hourly level (e.g. in the case of demand). It leads to providing the average annual values of all of the parameters for OSeMOSYS, even though the PLEXOS model is much more detailed and complex.

The model's alignment is provided for the same set of fuel, i.e. the one analysed in PLEXOS. As a result, geothermal and waste energy are not considered in the OSeMOSYS models anymore. At the same time, a general category of *coal* in OSeMOSYS is an aggregation of the *hard coal* and *lignite* fuels found in PLEXOS.

The most important change in the OSeMOSYS model from this report's point of view, is a lack of the originally modelled *annual limit of emissions*. The obtained values of CO_2 emissions are the result of the model's alignment and defining the parameters responsible for emissions modelling, e.g. carbon price. This constitutes an additional validation of the PLEXOS model and checks if the adjusted input but different model set-up, can provide reliable and comparable outcomes.

Additionally, the fourth *'New Policy'* scenario in OSeMOSYS is created for both Germany and Poland. This outline does not have its counterpart in the PLEXOS model since it is only used for the purpose of comparisons of the future trends of emissions. The scenario includes the targets of the long-term energy policies whose main assumptions are described in Appendix A. A common strategy for Germany and Poland is a higher implementation of renewables what is one of the measures to decrease CO_2 emissions. In that way, the scenario brings an insight to the report about the behaviour of emissions modelling in a power system model where some of the constraints are implemented and the model is forced to take into account the presumed actions. A detailed description of the model set-ups is available in Appendix C.

2.3. Reference Statistics

The historical values of CO_2 emissions between 2016-2017 returned by the PLEXOS and OSeMOSYS models, should be checked against the reference statistics. An abundance of referential sources is available online. However, their proper interpretation is crucial for a correct validation of the obtained model results.

For the purpose of this study, two main sources are chosen:

- European Union Transaction Log (EUTL), (EUTL, 2017);
- Eurostat (Eurostat, 2019).

Their detailed description, usage and understanding is described in the following sections of this chapter.

2.3.1. European Union Transaction Log (EUTL)

The Union Registry (European Commission, 2016b) is an online database that collects the stationary installations with the installed capacity exceeding 20 MW, as well as the aircraft operators, contributing to GHG generation. These units are grouped into 29 activities. A detailed description of the Union Registry and its components as a part of the EU ETS is available in Appendix A.

The most important activity for the Energy Sector is *No. 20. – Combustion of Fuels*. It gathers the condensing power plants and CHP units with a purpose of district heating or designed for an usage on industrial site. The category *No. 20* covers 961 units in Germany and 528 in Poland. A division between the units' types was investigated for the purpose of this study.

The EU Member States open accounts in the Union Registry and send the annual reports with the verified emissions on an utility level. The EUTL is responsible for recording these data and authorising the transactions of emission allowances. This system complies with the EU ETS and is part and parcel of that.

Conclusively, the EUTL database contains the list of the units with their assigned IDs, cumulative values of emissions, allowance allocation, status, permit ID/date and allowances' trade/reserve. It is available for each Member State on the annual level since 2005 (1st Phase of the EU ETS). By using the unit's ID, it is possible to match the verified emissions from the EUTL with other parameters (e.g. efficiency, operation dates, used fuel, etc.) from different statistics available online in order to create one extensive database useful for the energy system analysts. Among these sources collecting the data on a facility level there are:

- European Network of Transmission System Operators for Electricity (ENTSO-E), (ENTSO-E, 2019);
- Large Combustion Plants (LCP), (EEA, 2018a).

An example of such a database's construction is attached in Appendix D. It helps to assign the names of the units implemented in the PLEXOS model. In that way, the correct annual values of the emissions on a power plant level can be checked. It is also helpful to identify the missing or additional (retired, unused) units in the PLEXOS input.

The verified levels of emissions on a thermal installation level, are used by the European Environment Agency (EEA), (EEA, 2019), to prepare the annual reports indicating trends and projections in the EU ETS. Every year, top thirty most polluting combustion power plants are found. In the latest report from 2018 (EEA, 2018b), ten German combustion plants contributing to 46% share of the emissions among the top thirty most emitting EU installations in 2017, and seven Polish units accounting for 24% emissions accordingly, were included.

2.3.2. Eurostat Energy Balances

The second statistical source is the latest version (released in February 2019) of the energy balances for each of the EU Member States prepared by the Eurostat (Eurostat, 2019). It contains, among others, the fuel consumption needed to generate electricity on the annual level. By multiplying the fuel consumption and emission factors, the levels of CO_2 emissions can be estimated. The used values of the emission factors are default for all of the EU Member States (Koffi et al., 2017).

A scheme of the categories available in the Eurostat energy balances and relevant for this study is presented in Figure 3.

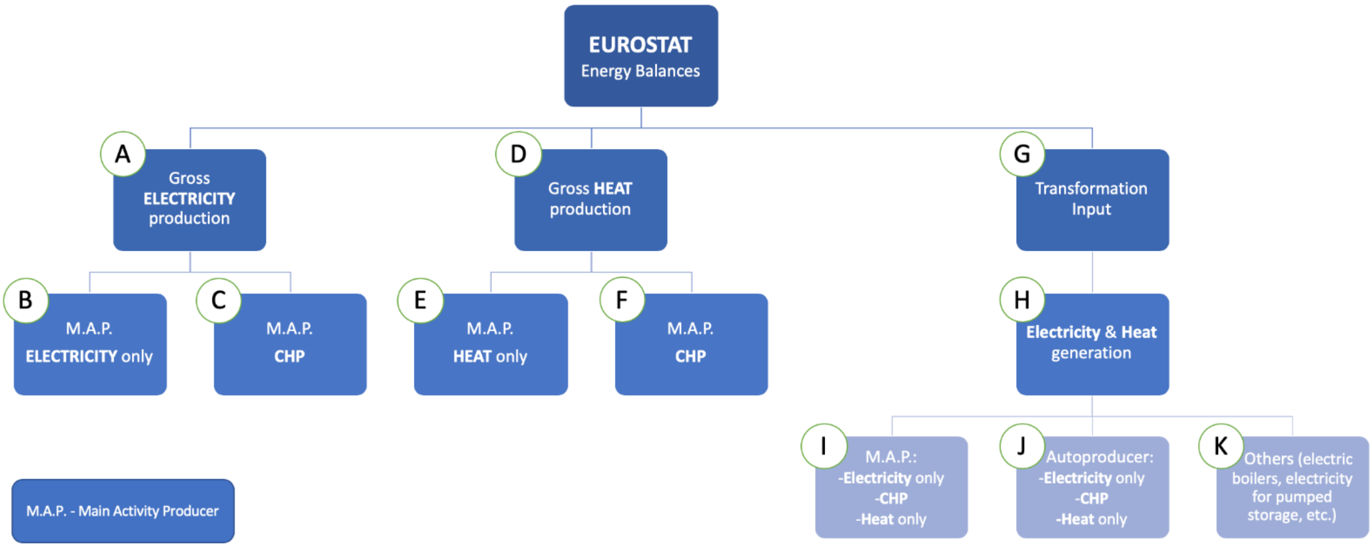


Figure 3: Scheme of the categories present in the Eurostat energy balances.

The emissions should cover the whole power production considered in the analysed models; thus, the calculations are based on the fuel consumption used for:

- Power generation in the condensing power plants;
- Power generation in the CHP units.

Fuel consumption for the *'Electricity and Heat production'* (category H in Figure 3) was multiplied with the corresponding emission factors for used fuels, what was followed by subtracting the emissions based on the *'Gross Heat production'* (category D in Figure 3). A small share of the *'Heat only production'* part in category H was neglected for both Germany and Poland.

2.4. Roadmap of the CO_2 validation

The following steps should be taken in order to validate a power system model with a special emphasis put on the returned values of CO_2 emissions:

1. Download the list of units from the used modelling software, e.g. PLEXOS.
2. Update the above list by checking the installed capacity according to the official, national statistics:
   - In the case of Poland, the annual reports prepared by the PSE (Polish Transmission System Operator), (PSE, 2019);
   - In the case of Germany, the reports published by the Federal Network Agency (Bundesnetzagentur), (Bundesnetzagentur, 2019).
3. If needed, update the remaining parameters, apart from the installed capacity, on a power plant level. It can be required in the case of a coal phase-out (Egenter, 2019), or limited units'

operation (what is also considered in the annual reports, (PSE, 2019)). Some parameters, e.g. start cost or variable operations and maintenance for the groups of power plants with a similar profile (fuel, efficiency), should be checked in the latest studies and eventually corrected. In the case of CO_2 emissions, the emission factors should be checked and updated – it can be done for all of the units separately or on a country level.

4. Download the annual report for the Member States, which is available in the Excel format at the website of the European Commission in the Union Registry tab (European Commission, 2016b). It contains the list of the units registered in the EUTL with their corresponding IDs, verified values of emissions, assigned allocations, traded allocations and reserves.[1]
5. Filter the data for a particular country and select as the Main Activity – *No. 20. Combustion of fuels* (detailed information about the activities of the EUTL in Appendix A).
6. Compare the above registry with the external database allowing to identify and regroup the condensing units, CHP ones and the facilities used for industrial purposes. Assigning the unit's type by comparing two databases might be also done by writing a proper script.
7. Check the emissions levels gathered in the EUTL registry for the matching power plants implemented to the analysed model. Update the latter if any are missing. Make sure that the model's results are obtained after rerunning it with all of the implemented changes/updates.
8. After checking the emissions on a power plant level, check the sum of emissions by aggregating the results for created three groups, i.e.:
   - Condensing units;
   - CHP;
   - Utilities used for industrial purposes.

   The above distinction can be done by writing a script filtering the names of the units – power plants or CHP units, as well as the names of assigned companies providing power/heat since the list of the heat providers on a national level is usually limited. This can significantly speed the whole process up but will not give the results free of errors. The names of some units are misleading, e.g. they can indicate a CHP unit whereas in the reality it is a condensing power plant.
9. Compare the emissions results gathered in the EU ETS registry with the ones obtained from the analysed model. Explain the possible mismatches.
10. Calculate the emissions based on the fuel consumption documented by the Eurostat in the country energy balances (Eurostat, 2019). This might be done by multiplying the fuel consumption and corresponding emission factors (Koffi et al., 2017).
11. Compare the analysed model with the other modelling tools, e.g. OSeMOSYS to check the continuation of the trends, RE development or genuineness of assumptions in the following years. Take into consideration different settings, input data, constraints, way of calculating the emissions, etc. in both of the models, what might have an impact on the final results.

The last two points constitute an additional validation step. The EUTL is a reliable database and is recommended to be considered as the main referential source. A correct establishment towards European strategies is a prerequisite for the Member States to follow a sustainable development meeting the set goals along the energy system transition.

The above roadmap of the CO_2 validation is available in a graphical form, attached in Appendix E.

[1] As an alternative, it is possible to write a script gathering the information from the EUTL database (EUTL, 2017). However, the verified emissions are cumulative, thus assessing the emissions for a selected year requires also downloading the data for one year prior to the analyzed period and subtracting the corresponding values.

3. Results and Discussion

This chapter presents selected and the most relevant results for this study. Complementary results are available in Appendix D for statistics and Appendix F for PLEXOS and OSeMOSYS models.

3.1. Statistics

The first section related to the EU ETS, summarizes the information available in the EUTL database enriched with own calculations. The second part contains the calculations of CO_2 emissions based on the fuel consumption documented in the Eurostat energy balances.

3.1.1. EUTL

The category *No. 20 – Combustion of fuels* was selected as the one relevant for this study among 29 activities present in the EU ETS. Table 1 and 2 below gather a division of the thermal installations within this category for Germany and Poland accordingly. The EUTL gives only information about the annual verified emissions on a combustion plant level.

The detailed tables with listed condensing power plants and their verified emissions in 2016 and 2017 from the EUTL database for both Poland and Germany, are available in Appendix D.

EUTL - Germany							
Units belonging to the Category *No. 20. – Combustion of fuels*	Unit's type	Number	% of total number	Emissions in 2016 [Mt_{CO2}]	% of total emissions 2016	Emissions in 2017 [Mt_{CO2}]	% of total emissions 2017
	Condensing PP[2]	85	8.84%	223.75	71.09%	206.93	70.06%
	Condensing PP_IND	45	4.68%	14.57	4.63%	14.93	5.05%
	CHP_DH	344	35.80%	39.55	12.57%	37.06	12.55%
	CHP_IND	487	50.68%	36.89	11.72%	36.43	12.33%
	TOTAL	**961**	**100%**	**314.77**	**100%**	**295.36**	**100%**

Table 1: Division of the thermal installations covered by the activity No. 20 in the EUTL for Germany in 2016 and 2017 (own elaboration based on (European Commission, 2016b)).

In Germany, among 961 registered units and belonging to the category *No. 20* (Table 1), only 8.84% are condensing power plants. At the same time, these units generate the biggest part of emissions, i.e. 71.09% in 2016 and 70.06% in 2017. The CHP units which are the most numerous groups, 344 installations for district heating and 487 for industrial purposes, contributed to only 12.57% and 11.72% of verified emissions in 2016. Nearly half of the German condensing power plants, i.e. 45 installations, are used to generate electricity for industrial purposes exclusively. These units contributed to 4.63% in 2016 and 5.05% next year of verified emissions within the category *No. 20* of the EUTL.

[2] *Condensing PP* stands for the condensing power plants; *PP_IND* – power plants used by the industries; *CHP_DH* – CHP units with a district heating mode; *CHP_IND* – CHP units used by the industries.

EUTL - Poland							
Units belonging to the Category *No. 20. – Combustion of fuels*	Unit's type	Number	% of total number	Emissions in 2016 [Mt_{CO2}]	% of total emissions 2016	Emissions in 2017 [Mt_{CO2}]	% of total emissions 2017
	Condensing PP	23	4.36%	107.16	67.78%	108.79	68.07%
	Condensing PP_IND	1	0.19%	0.031	0.02%	0.034	0.02%
	CHP_DH	302	57.20%	31.09	19.67%	31.38	19.64%
	CHP_IND	202	38.26%	19.81	12.53%	19.61	12.27%
	TOTAL	**528**	**100%**	**158.09**	**100%**	**159.81**	**100%**

Table 2: Division of the thermal installations covered by the activity No. 20 in the EUTL for Poland in 2016 and 2017 (own elaboration based on (European Commission, 2016b)).

In Poland, among 528 thermal installations belonging to the Union Registry, only 23 are condensing power plants (Table 2). These units emitted 67.78% in 2016 and 68.07% in 2017 of the annual verified emissions reported by the combustion plants. A share of emissions generated by the CHP units, 302 installations for district heating and 202 for industrial purposes, was lower, at the level of 19.67% and 12.53% respectively in 2016. Only one power plant in Poland is fully used to generate electricity for the industrial purposes but its emissions constitute less than 1% of the annual emissions within considered category of the EUTL.

3.1.2. Eurostat

Eurostat as the second referential source (i.e. after EUTL), and used to verify the levels of historical emissions in 2016 and 2017, provides the energy balances with the fuel consumption for power generation on a country level. Thus, the calculated emissions are only an approximation of the real values and give a range of possible total emissions emitted by the combustion plants.

The used emission factors, as well as the calculated emissions per each fuel in 2016 and 2017 for both Germany and Poland, are available in the tables attached in Appendix D.

Tables 3 and 4 below summarize the results of the calculated total annual emissions by using the method described in Chapter 2.3.2., for Germany and Poland accordingly. They contain also the results of the emissions obtained in the three analysed model set-ups of the PLEXOS model. The latter considers both the condensing power plants and CHP installations, i.e. total absolute values.

GERMANY – Annual Emissions [Mt]		
	2016	**2017**
Eurostat	283.00	264.15
PLEXOS *'Base Case'* set-up	296.84	271.80
PLEXOS *'New Emission Factors'* set-up	300.54	274.43
PLEXOS *'EUTL stack'* set-up	293.16	268.47

Table 3: Comparison of the calculated annual electricity-related CO_2 emissions in Germany in 2016 and 2017 based on the fuel consumption documented in the Eurostat (own elaboration based on (Eurostat, 2019)), with the results obtained in three analysed PLEXOS model set-ups.

In the case of Germany, the emissions obtained in *the 'EUTL stack'* model set-up are the closest to the values calculated from the fuel consumption in Eurostat (Table 3). This is an effect of analyzing the same set of condensing power plants in this model set-up as in the EUTL database which is a reliable reference. Additionally, more precise emission factors calculated for German fuels are applied. Significantly high emissions in the PLEXOS model set-ups comparing to the Eurostat, can be caused by accordingly higher power generation by the modelling set-up than in the reality or too much installed capacity of the condensing power plants and their full operation, whereas not all of the units use their total installed capacity all year round.

Another explanation of any deviations between the results are the simplified and quite general emission factors used for emissions calculation based on the fuel consumption in Eurostat energy balances. They are unified and used by the EU ETS. Nevertheless, the emissions vary significantly depending on the consuming fuel quality within a country. Moreover, the emissions calculations based on the Eurostat are simplified by considering only the main groups of fuel. In the reality the used fuels are more diversified.

In the case of Poland (Table 4), the results of CO_2 emissions in all of three PLEXOS model set-ups are relatively close to the ones calculated by using the fuel consumption gathered in the Eurostat energy balance. Choosing one model set-up with the prevailing and explicitly best results is not justified.

POLAND – Annual Emissions [Mt]		
	2016	**2017**
Eurostat	124.47	125.26
PLEXOS *'Base Case'* set-up	119.09	126.18
PLEXOS *'New Emission Factors'* set-up	119.47	126.77
PLEXOS *'EUTL stack'* set-up	118.59	124.45

Table 4: Comparison of the calculated annual electricity-related CO_2 emissions in Poland in 2016 and 2017 based on the fuel consumption documented in the Eurostat (own elaboration based on (Eurostat, 2019)), with the results obtained in three analysed PLEXOS model set-ups.

The PLEXOS model for Poland is much smaller, e.g. in terms of installed capacity, comparing to the one developed for Germany. It is reflected in the fewer provided changes between the model set-ups what in turns has got less impact on the results.

The explanation of the results' differences is the same as in the Germany's case. However, a close range of values obtained both in the PLEXOS model set-ups and Eurostat, confirms that the applied method of emissions calculation is based on the correct assumptions.

3.2. Optimization models

The first section contains a comparison of the annual CO_2 emissions on a national level for both historical and future time periods, across model set-ups developed in PLEXOS and OSeMOSYS.

The next part pertains to correlations between emissions, fuels, generated power and emissions intensity per fuel among created model set-ups.

The last part assesses top ten most emitting combustion plants in Germany and top seven Polish installations according to the EEA 2018 report (EEA, 2018b). This section contains only the PLEXOS results since lack of individually modelled power plants in OSeMOSYS hinders a relevant analysis.

3.2.1. Total annual emissions

Figure 4 and 5 below present the total annual values of historical CO_2 emissions in 2016 and 2017 across analysed model set-ups in Germany and Poland, accordingly. The models' results are compared with the emissions calculated from the fuel consumption documented in the Eurostat energy balances. This reference source enables the user to estimate the level of national electricity-related emissions generated in the condensing power plants and the CHP units, without an influence of district heating. In that sense, the Eurostat database is a better source to validate the whole power system model since the EUTL covers both electricity- and heat-related emissions from the CHP units. Another comparison of the electricity-related emissions only from the condensing power plants obtained in the three analysed PLEXOS model set-ups and the EUTL as a referential source, is attached in Appendix F.

a) b)

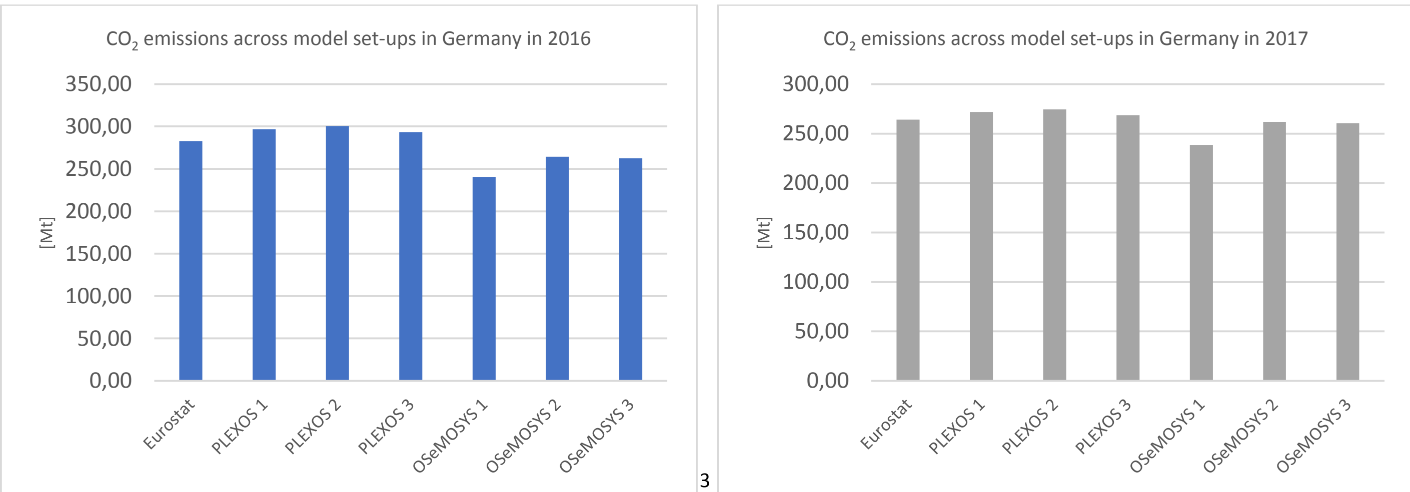


Figure 4: Annual CO_2 emissions in Germany in a) 2016, b) 2017, across Eurostat, three PLEXOS and three OSeMOSYS model set-ups.

The PLEXOS model's results for Germany for 2016 and 2017 are explicitly higher than the values in Eurostat (Figure 4). The differences in 2016 are at the level of 4.9% in the case of 1st model set-up ('PLEXOS 1'), i.e. *'Base Case'*; 6.2% for the 2nd model set-up ('PLEXOS 2'), i.e. *'New Emission Factors'*; 3.6% in the 3rd case ('PLEXOS 3') for *'EUTL stack'* model set-up. The lower percentage change across PLEXOS model set-ups comparing to the reference case is seen in 2017. A table with the exact values of obtained CO_2 emissions from the whole power system models built in PLEXOS and OSeMOSYS with the percentage changes referring to the Eurostat as the base case, is attached in Appendix F.

The higher results in PLEXOS can be explained by the fact that some of the power plants emit more CO_2 emissions than it was documented in the EUTL in 2016 and 2017. This is a result of using the whole installed capacity throughout the whole year by the model, whereas in reality the operation of some units is limited. Even though the capacities are updated for all of three model set-ups, the model is not free of assumptions. Thus, a careful validation should be done on a power plant level to indicate

---

[3] PLEXOS 1, -2, -3 refers to the consecutive model set-ups, i.e. *'Base Case', 'New Emission Factors, 'EUTL stack'*; by analogy the same abbreviations are applied for the OSeMOSYS model set-ups.

the units which emit more than in the reality and on the contrary, the ones returning 0-values of CO_2 emissions in the model but in fact their impact on the national emissions was documented in the EUTL.

The opposite pattern of the results can be seen in the case of OSeMOSYS model built for Germany. The emissions in all three created model set-ups are lower than the ones calculated from the Eurostat database. Looking at the results for 2016, in the 1st OSeMOSYS model set-up ('OSeMOSYS 1' in Figure 4) the emissions are 15.0%, in the 2nd model set-up 6.6% and in the 3rd one 7.2% lower than in the Eurostat. Relatively slighter percentage differences are observed for 2017, where in the case of *'New Emission Factors'* model set-up the CO_2 emissions are only 0.8% lower than in the reference case. The main explanation of the lower results returned by the model is its high vulnerability to changes. It was observed that even a small adjustment of the *Residual Capacity* (i.e. installed capacity per technology), had an impact on the emission results. The second factor affecting the output are the set emission factors. Their impact can be especially seen while comparing the 1st and 2nd model set-ups which differ from each other only by this particular parameter. The original emission factors set in the *'Base Case'* model set-up in the OSeMOSYS model are too low comparing to the ones used in PLEXOS what causes an additional difference. At the same time, the unified, i.e. higher than original, emission factors and not fully adjusted residual capacities in the 2nd model set-up make its results the highest across all analyzed cases.

The results of CO_2 emissions across model set-ups created for the Polish models (Figure 5) indicate a similar pattern as in the Germany's case. The output of the PLEXOS model is higher or close to the Eurostat values, whereas the emissions modelled by the OSeMOSYS are lower than the reference case. A very good match of the PLEXOS model set-ups to the Eurostat can be expressed by the percentage differences, in 2016 they at the level of 4.7-4.0% and for 2017 the changes are around 1.2-0.6% across three analyzed model set-ups. The emissions modelled by OSeMOSYS show higher deviations, up to 28.4% in 2016 and even up to 31.6% for the *'Base Case'* model set-up in 2017. A complete table with the modelling results and corresponding percentage changes of the model set-ups to the referential source is attached in Appendix F.

a) b)

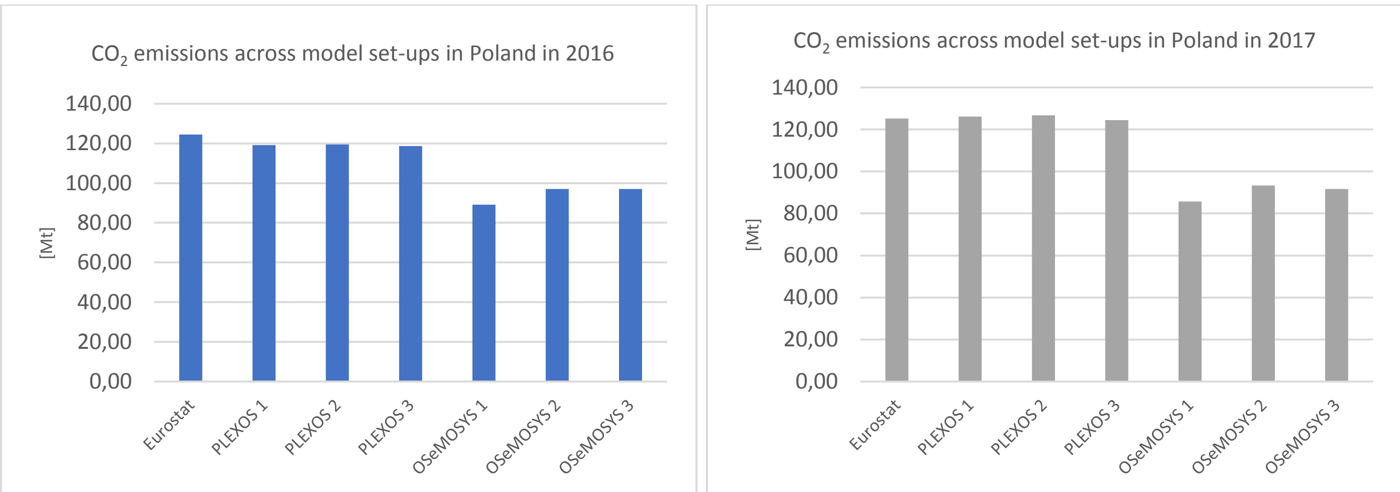


Figure 5: Annual CO_2 emissions in Poland in a) 2016, b) 2017, across Eurostat, three PLEXOS and three OSeMOSYS model set-ups.

The model built for Poland is significantly smaller comparing to the one built for Germany in PLEXOS or OSeMOSYS. The installed capacity in 2016 in the *'Base Case'* model set-up of the models for Poland is at the level of 41.6 GW, versus 143.7 GW in Germany. Thus, any changes in the installed capacity are even more visible in the model's output. As expected, the *'New Emission Factors'* model set-up indicates the highest results by applying the unified and updated emission factors for the fuels.

The second part of the PLEXOS model validation looks into the trends of CO_2 emissions in the near future, i.e. years 2019-2025. Figure 6 below presents the trends of predicted emissions across three PLEXOS model set-ups and four OSeMOSYS cases for Germany. The column charts showing the magnitude of emissions for each year between model set-ups, the line charts with a separate close-up on the PLEXOS and OSeMOSYS results, as well as the percentage changes between the model set-ups stating the PLEXOS *'Base Case'* as the referential one, are attached in Appendix F.

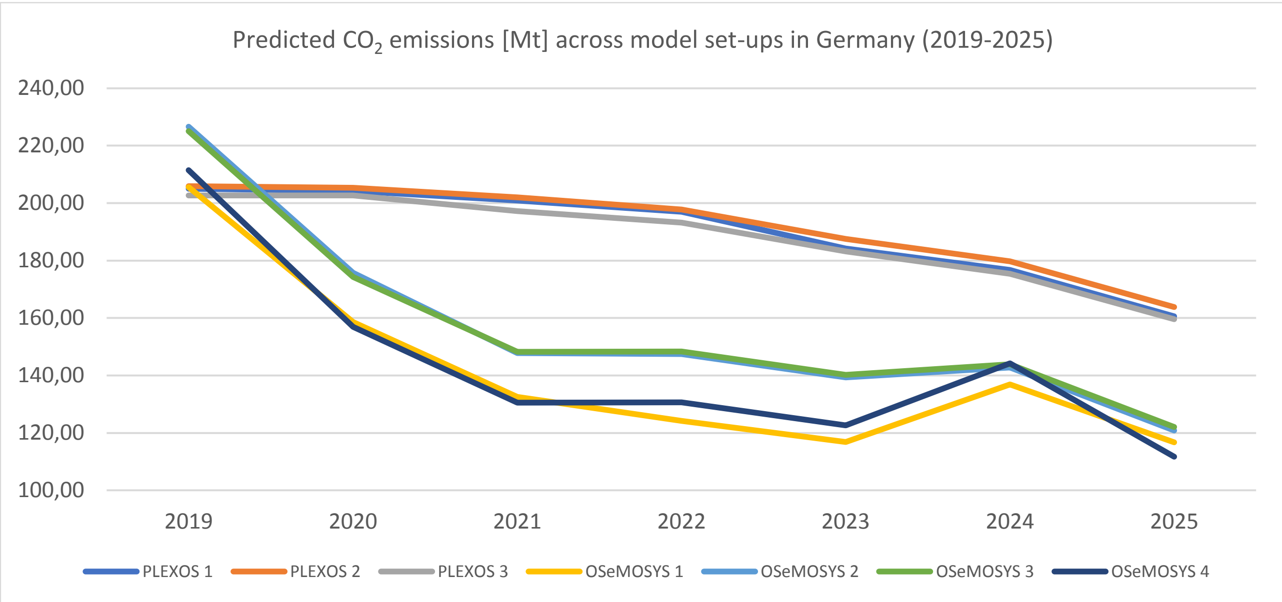


Figure 6: Predicted CO_2 emissions [Mt] across PLEXOS and OSeMOSYS model set-ups in Germany (2019-2025).

The modelled CO_2 emissions in the near future are higher in all of the PLEXOS model set-ups than it takes place in the OSeMOSYS model for Germany (Figure 6). Moreover, the results indicate the same decreasing trend within two modelling software. The PLEXOS model forecasts a stable drop with the years, whereas there is an explicit peak of emissions in 2024 in OSeMOSYS. This is caused by an increased power generation from the coal-fired combustion plants in that particular year, as well as investing in the technologies using natural gas due to the upcoming coal phase-out in Germany by the end of 2038.

As expected, the *'New Emission Factors'* case in both software programs returns the highest results of CO_2 emissions over the analyzed time period by applying higher emission factors, i.e. producing more emissions per 1 MWh of generated electricity. At the same time, the 3rd model set-up, i.e. *'EUTL stack'* displays the lowest emissions across the PLEXOS model set-ups and the highest ones in the case of OSeMOSYS. The opposite pattern is a result of different model set-ups in terms of modelling the CHP units since the 3rd model set-up assumes an increased electricity generation in the cogeneration mode and less from the condensing power plants. A different structure of the used software and ways of defining the same parameters hinders from an exact alignment what results in the differences between the outputs.

The 4th OSeMOSYS scenario, i.e. *'New Policy'*, aims to predict the level of emissions by forcing the model to implement the changes proposed by the policy makers. The national energy strategies underline an importance of stronger introduction of renewables; thus, lower CO_2 emissions are expected. However, despite setting the renewable targets as an increased share of renewables in the electricity generation and an augmented development of offshore wind-based power generation (a detailed description in Appendix C), the predicted emissions are slightly lower only between 2020-2021 than in the *'Base Case'* model set-up and clearly higher in the following years. It confirms that these particular actions do not bring a desired effect and investing in them is not profitable.

A comparison of the predicted CO_2 emissions trends across model set-ups along the analyzed timeframe (2019-2025) for Poland is depicted in Figure 7 below. The additional and more detailed collations of annual emissions for each year between the model set-ups, percentage changes and the separate line charts with the emissions trends for both software are attached in Appendix F.

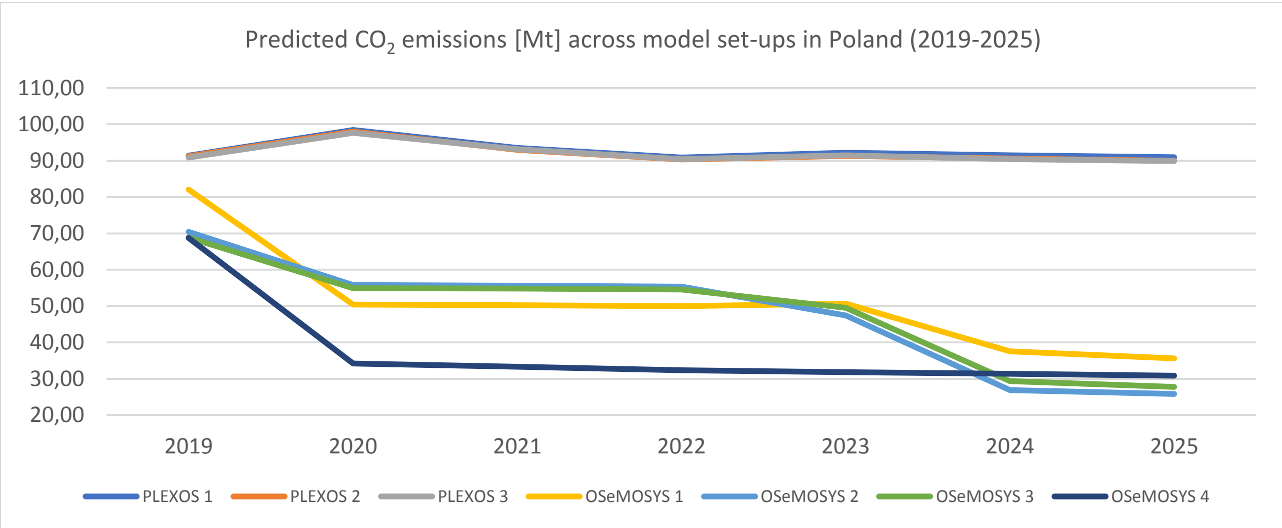


Figure 7: Predicted CO_2 emissions [Mt] across PLEXOS and OSeMOSYS model set-ups in Poland (2019-2025).

The PLEXOS results do not differ significantly between the model set-ups, the maximum differences are at the level of 2.0%, whereas the differences between OSeMOSYS model set-ups reach even 20.0%. The PLEXOS model assumes a stable and mild decrease of emissions with the years with one explicit peak in 2020. Higher emissions in that year are caused by installing additional coal and lignite-based capacities. At the same time, there is an opposite trend modelled by OSeMOSYS. Once again, a simplified models' alignment and quite general form of the OSeMOSYS model comparing to the PLEXOS one causes the differences in the results. An aggregation of the power plants in OSeMOSYS does not allow to set more detailed capacity targets or changes in the operation dates. This in turns affects the model's behavior. The OSeMOSYS model assumes a strong emissions reduction in the first modelling years because of setting the *Emission Penalty* parameter (i.e. carbon price).

The 4th scenario created in OSeMOSYS, i.e. *'New Policy'*, indicates the steepest drop of emissions in the considered timeframe among the analyzed model set-ups. This is a result of forcing the model to invest more in the technologies using biomass, geothermal energy, onshore wind and nuclear (a detailed description in Appendix C). This example shows that proposed changes by the energy policy makers are expected to bring a positive outcome in terms of emissions reduction.

3.2.2. Correlations between the results on a national scale

In this section, the emissions and power generation per fuel are analysed on a national level. Figures 8 and 9 contain a comparison of the results obtained in three different PLEXOS model set-ups and the reference statistics – Eurostat (Eurostat, 2019), for Germany. The latter was chosen because of the electricity-related emissions derived from both, the condensing power plants and CHP units, i.e. the whole PLEXOS model. This in turns has got a reflection in the national total power generation. The following comparison does not contain the OSeMOSYS results due to a lack of the lignite and hard coal fuels used in the model but only applying one common category – *coal*. A relevant comparison with the OSeMOSYS results can be found in the next section of this report.

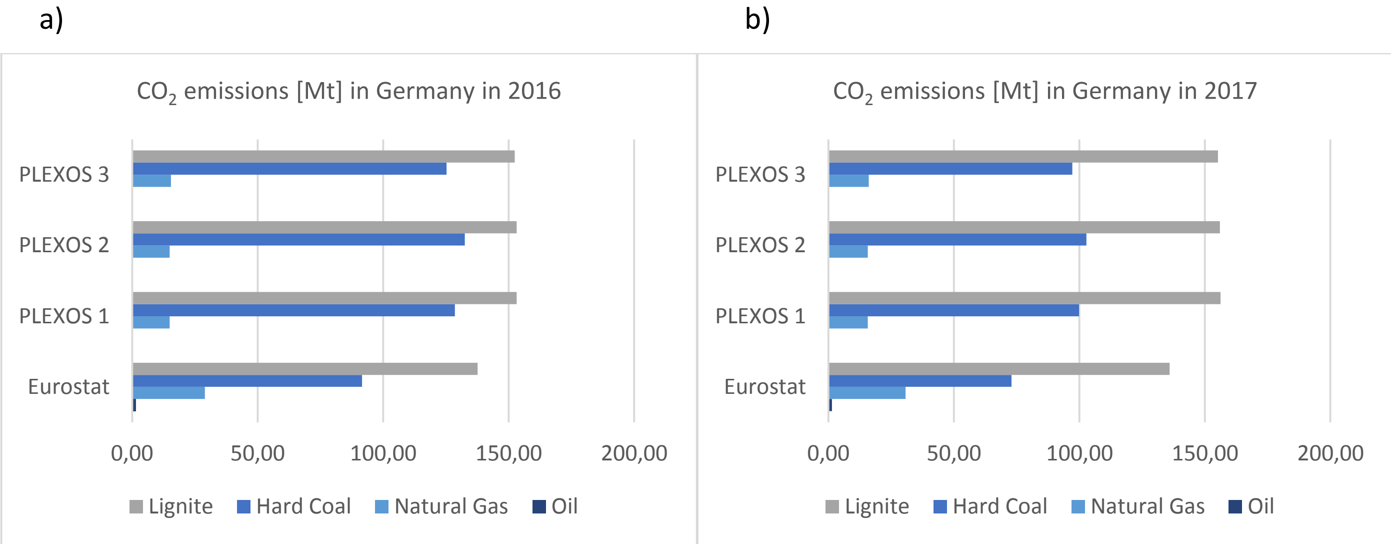


Figure 8: CO_2 emissions in Germany per fuel in a) 2016, b) 2017; among Eurostat and three PLEXOS model set-ups.

In Germany, eight out of the top ten most emitting power plants in 2017 are lignite-fired. On a national scale, most of emissions come from this fuel source what can be seen in Figure 8. The results of lignite-derived emissions in all of three PLEXOS model set-ups are higher in 2016 and 2017 than in the Eurostat. However, the power generation from the lignite-based units shows an opposite pattern, slightly higher values of power generation in Eurostat than in the PLEXOS model set-ups (Figure 9). It confirms that the PLEXOS model underestimates the power generation from the lignite-fired installations.

Almost 50% less emissions and 25% less power generation for natural gas units, and almost 100% underestimation for oil, can be seen in Figures 8 and 9 accordingly. These two fuels are also underestimated by PLEXOS comparing to the higher values stated in the reference statistics.

An opposite pattern, i.e. overestimating the power production in the PLEXOS model set-ups is visible for the hard coal-fired combustion plants (Figure 9). It is followed by increased emissions from the units fired with hard coal (Figure 8).

a) b)

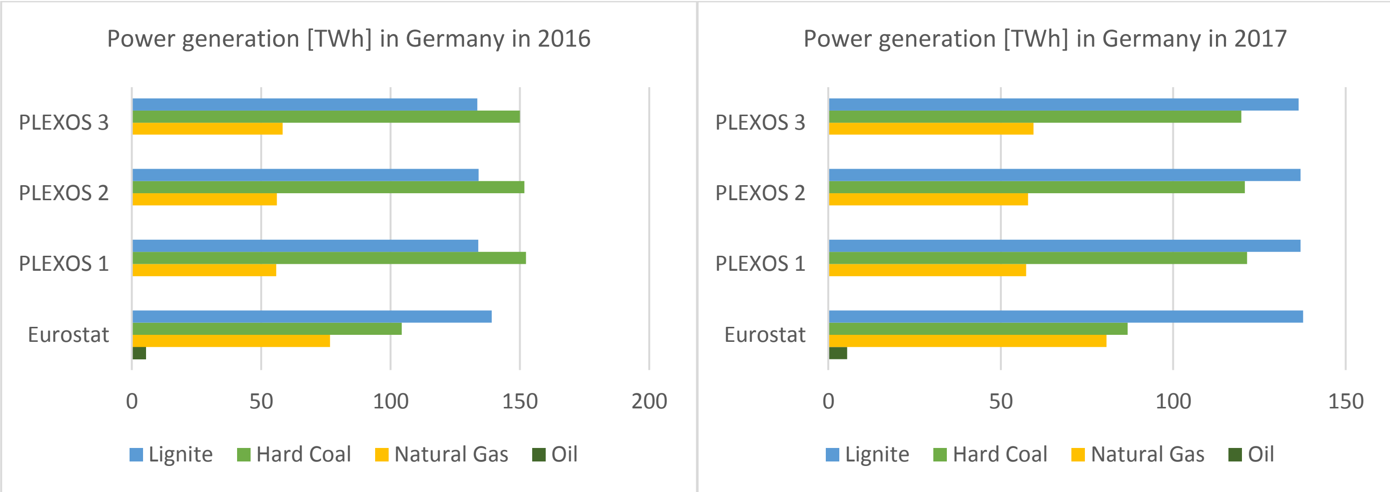


Figure 9: Power generation in Germany in a) 2016, b) 2017; among Eurostat and three PLEXOS model set-ups.

As expected, the 3rd PLEXOS model set-up, i.e. *'EUTL stack'* returns the closest results to the values gathered in the reference statistics. This model set-up contains the same set of condensing power plants as the ones listed in the EUTL database. At the same time, the values of power generation in the Eurostat reference balances cover the electricity generation' units only.

In Poland, the correlations between fuels and emissions (Figure 10), followed by a relationship between fuels and power generation (Figure 11), are also visible.

a) b)

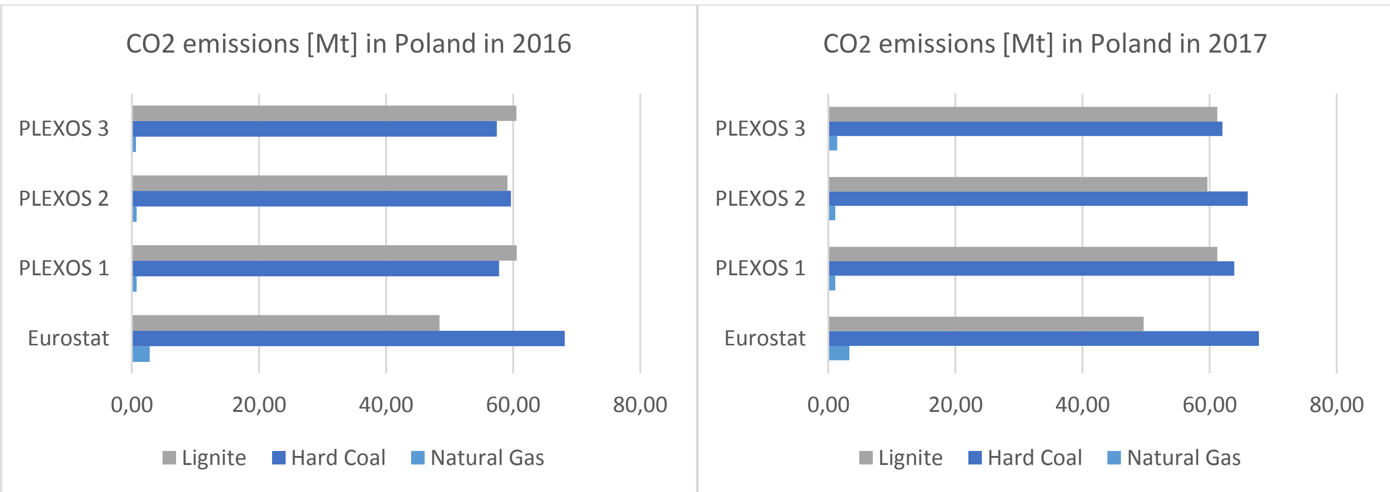


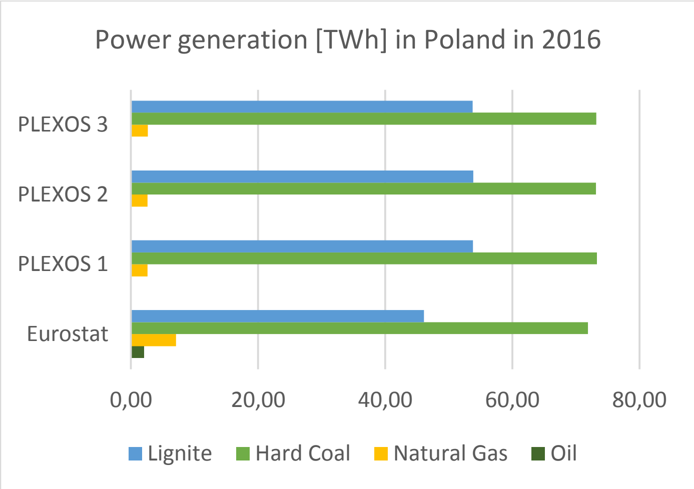
Figure 10: CO_2 emissions in Poland per fuel in a) 2016, b) 2017; among Eurostat and three PLEXOS model set-ups.

Even though the hard coal-derived emissions in all of three PLEXOS model set-ups in 2016 and 2017 are lower than in the Eurostat (Figure 10), the corresponding power generation in these years (Figure 11) indicates a strong overestimation of the hard coal-based units' operation in the PLEXOS model.

The differences of the emissions generation from the natural gas-fired power plants between the PLEXOS model set-ups and reference statistics, are caused by insufficient installed capacity in PLEXOS. This leads directly to much lower power generation from the natural gas-fired installations. The same situation and explanation is valid for the oil-based power units which are a relatively rare solution in terms of power generation in Poland.

A visible overestimation of the power generation in PLEXOS model can be seen for the lignite-fired combustion plants. This results in adequately higher emissions generation from these units comparing to the referential database.

a) b)



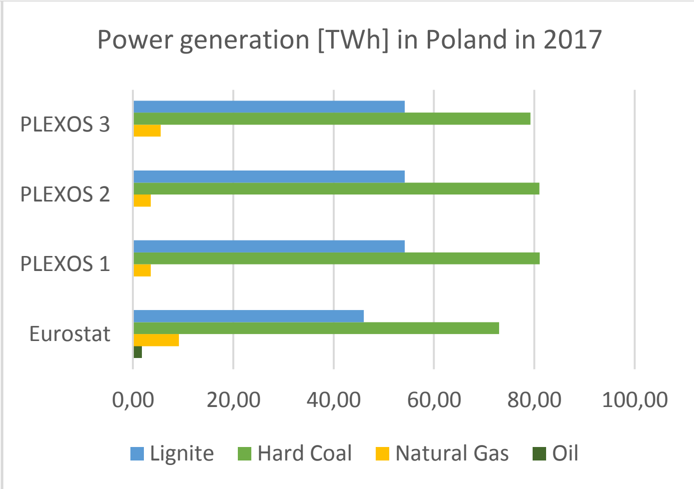
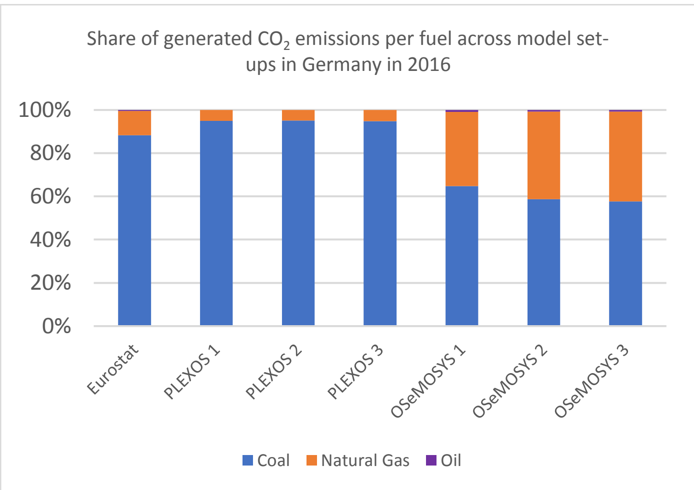


Figure 11: Power generation in Poland in a) 2016, b) 2017; among Eurostat and three PLEXOS model set-ups.

By analogy, the emissions per fuel are calculated for the model set-ups created in the OSeMOSYS models. Their percentage shares in the total national emissions obtained for Germany and Poland, are presented in the graphs below. However, no distinction between hard coal nor lignite in OSeMOSYS, resulted in the creation of one broad category – *coal*. Accordingly, the emissions obtained in the PLEXOS model set-ups for the *coal* as a fuel, are an aggregation of the hard coal- and lignite-based emissions.

A comparison of the emissions derived from coal, natural gas and oil, among Eurostat as the reference case, three PLEXOS and three OSeMOSYS model set-ups for Germany in 2016 and 2017, is illustrated in Figure 12 below.

a) b)



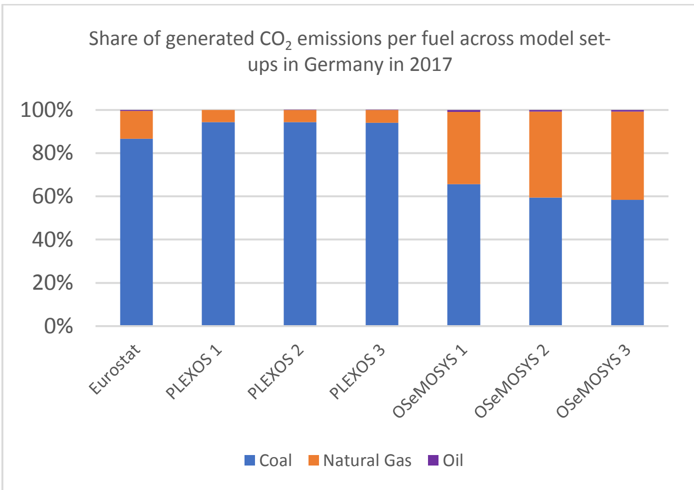


Figure 12: Share of generated CO_2 emissions per fuel across Eurostat, PLEXOS and OSeMOSYS model set-ups in Germany in a) 2016, b) 2017.

In the case of model set-ups created in PLEXOS, most of emissions come from coal combustion. There are also almost twice as less emissions derived from natural gas-fired installations than in the referential source. This pattern is visible for both 2016 and 2017. At the same time, the share of natural gas-based emissions in the OSeMOSYS model set-ups is almost twice bigger than it takes place in the Eurostat database.

A comparison of the emissions derived from coal, natural gas and oil across Eurostat, as well as PLEXOS and OSeMOSYS model set-ups in 2016-2017 for Poland, can be seen in Figure 13 below. The trivial differences (up to 3.8%), between emissions derived from the last two fuels, resulted in enlarging the *y axis'* scale (from 94% to 100%) to depict the occurred changes carefully.

a) b)

Figure 13: Share of generated CO_2 emissions per fuel across Eurostat, PLEXOS and OSeMOSYS model set-ups in Poland in a) 2016, b) 2017.

Most of emissions in all of the model set-ups come from coal combustion, as an aggregation of the emissions derived from hard coal and lignite combustion in the case of PLEXOS model. According to the fuel consumption data gathered by Eurostat, 1.07% in 2016 and 0.97% of oil-based emissions were generated in Poland. At the same time, neither PLEXOS nor OSeMOSYS demonstrated the emissions derived from this fuel. A relatively small installed capacity of the natural gas-fired installations in Poland results in low emissions from this fuel, at the level of 2.3% in 2016 and 2.7% in 2017 according to the Eurostat. These emissions are even 76.4-67.4% lower in the PLEXOS model set-ups and are not reported by almost any of the OSeMOSYS model set-ups at all. The only one exception is the *'EUTL stack'* case for Poland, which returns only 18% lower values of natural gas-based emissions than it was reported to the Eurostat.

The above observations for Germany and Poland confirm that the PLEXOS and OSeMOSYS models dispatch differently although they are aligned in terms of capacity and techno-economic characteristics. Some of the emissions results on a national scale vary by only 1% between the corresponding model set-ups. However, there are no correlations between the emissions per fuel what is a result of different principle of working of these two optimization tools.

3.2.3. Top emitting combustion plants

The emissions from the top ten emitting combustion plants in Germany in 2016 and 2017 are presented in Figure 14. The results from two sources, i.e. EUTL and PLEXOS *'New Emissions Factors'* model set-ups are referred. The latter was chosen due to its closer emissions results to the ones stated in the reference statistics, obtained by applying national emissions factors specified for Germany. In this way, *'New Emission Factors'* case constitutes a better reference point than the *'Base Case'* model set-up. A table with datapoints used for the figures' creation can be found in Appendix F.

a) b)

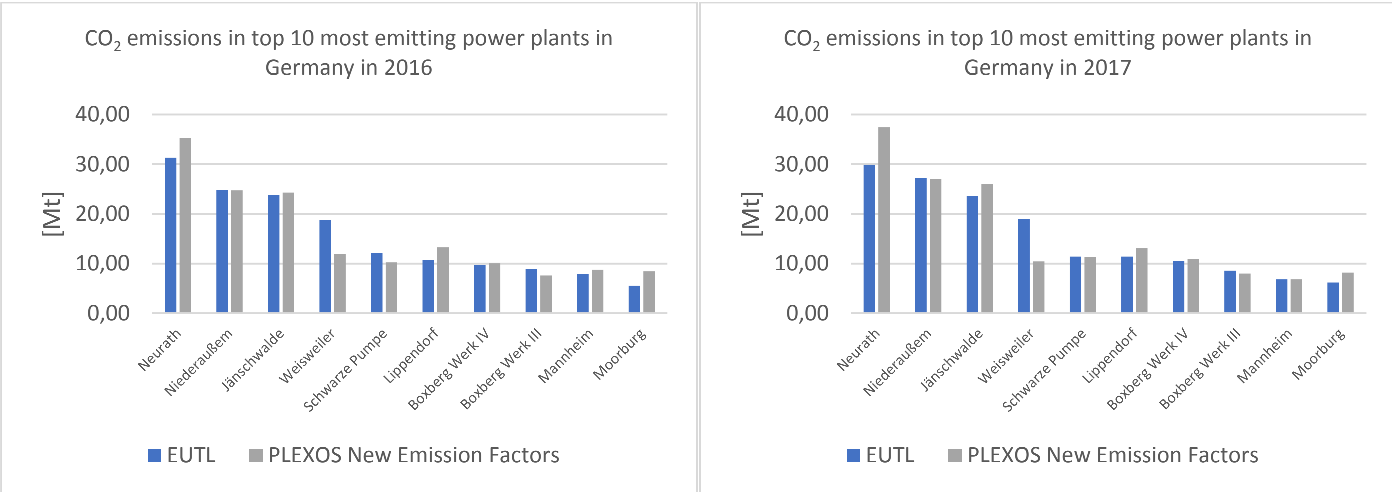


Figure 14: Comparison of CO_2 emissions generated by top ten most polluting combustion plants in Germany in a) 2016, b) 2017, among EUTL and three PLEXOS model set-ups.

In most of the power plants analyzed in Figure 14, the emissions obtained in the *'New Emission Factors'* model set-up are higher than in the EUTL. It is followed by increased power generation in the corresponding units what can be seen in Figure 15.

a) b)

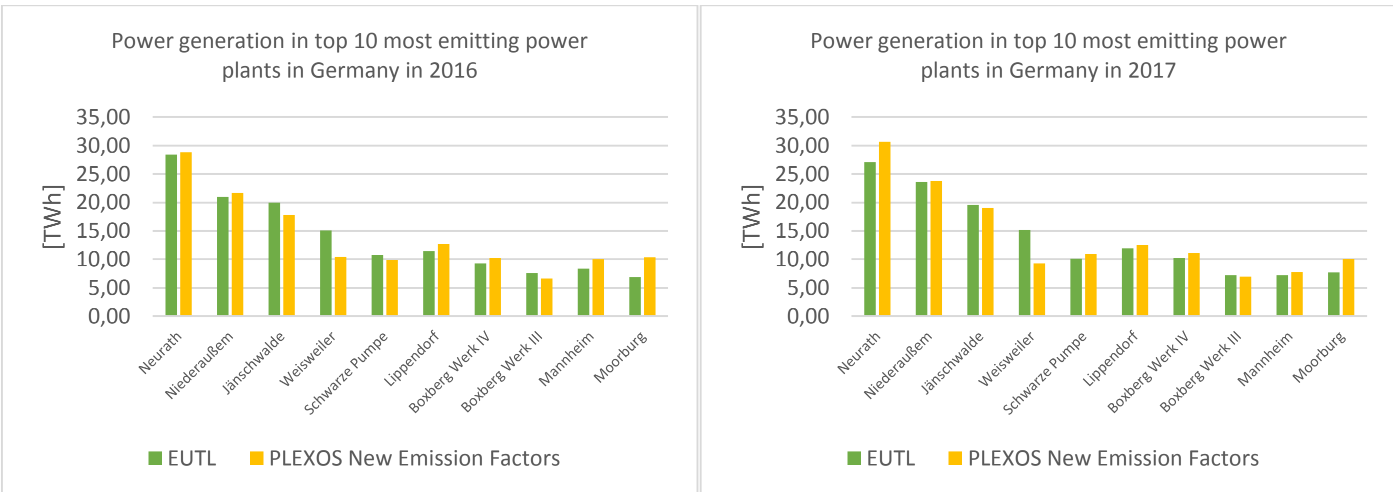


Figure 15: Comparison of power generation in top ten most polluting combustion plants in Germany in a) 2016, b) 2017, among EUTL and three PLEXOS model set-ups.

First eight combustion plants present in Figures 14 and 15 run on lignite fuel. The emission intensity for lignite is higher than that for hard coal, and in case of the most emitting German combustion plant in 2017, i.e. Neurath, was at the level of 1.2 [t_{CO2}/TWh] (EEA, 2018b). The emission intensity of the same plant in the *PLEXOS 'New Emission Factor'* model set-up was even higher, at 1.22 [t_{CO2}/TWh] in 2017 (Appendix E). It explains higher emissions returned by the PLEXOS model than stated in the EUTL. What is more, PLEXOS assumes the full unit's operation all year round, resulting in increased power generation.

The last two combustion plants, i.e. Mannheim and Moorburg use hard coal as the main fuel. Both, emissions and power generation are higher in the 2nd PLEXOS model set-up than in the EUTL being the reference statistic. In spite of using the same fuel, visible differences between these two power plants in terms of CO_2 emissions followed by power generation, depend on installed capacity and emission intensity (accurate datapoints in Appendix E).

The EEA indicated the top seven emitting combustion plants in Poland among thirty most polluting installations in the EU in 2017 (EEA, 2018b). Their verified emissions in 2016 and 2017 by the EUTL and compared with the results obtained in the *'New Emission Factors'* model set-up, are set in Figure 16. A table with datapoints used for the figures' creation can be found in Appendix F.

a) b)

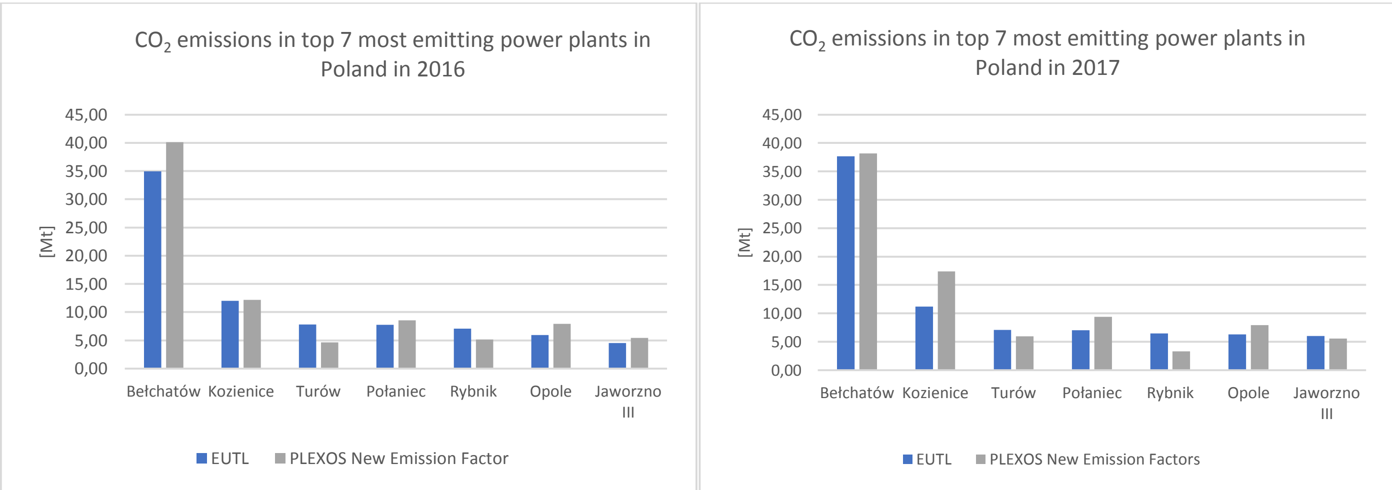
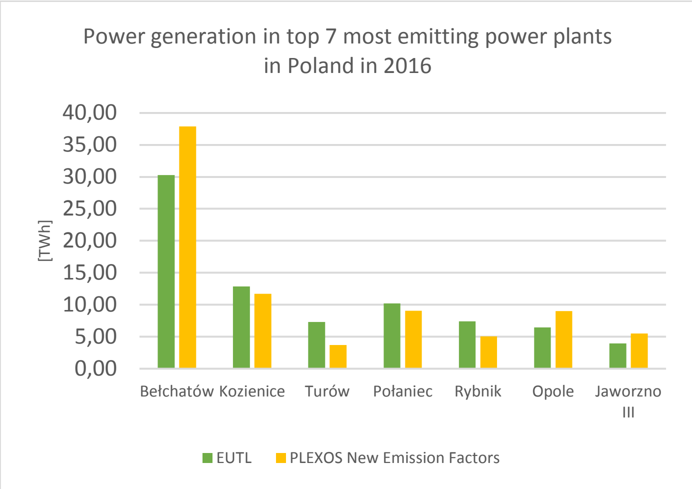


Figure 16: Comparison of CO_2 emissions in generated by top seven most polluting combustion plants in Poland in a) 2016, b) 2017, among EUTL and three PLEXOS model set-ups.

Only two out of seven indicated combustion plants are lignite-fired, i.e. Bełchatów and Turów, the rest uses hard coal as the main fuel. Even though the emission intensity of the Bełchatów power plant in 2016 was lower in the PLEXOS *'New Emission Factors'* model set-up, i.e. 1.06 [t_{CO2}/TWh] than reported by the EUTL, 1.10 [t_{CO2}/TWh], the emissions returned by PLEXOS are much higher. It is followed by the increased power generation what can be seen in Figure 17 below. These differences can be explained by higher installed capacity in the PLEXOS model (5442 MW in 2016) than it was reported to the EUTL (5030 MW).

The opposite pattern indicated by lower emissions and power generation in the 2nd PLEXOS model set-up than in the EUTL database, can be seen for the Turów and Rybnik power plants. In the first case, it is caused by much lower installed capacity provided in the PLEXOS modelling set-up, i.e. 965 MW in 2016 instead of 1488 MW reported to the EUTL. However, despite the higher installed capacity of the Rybnik power plant in PLEXOS modelling set-up (1720 MW in 2017) than in the EUTL database (1555 MW), the emissions are lower in the PLEXOS *'New Emission Factors'* case. The emission intensity is also higher in the case of PLEXOS model set-up, i.e. 1.01 comparing to 0.99 [t_{CO2}/TWh] in the EUTL. The differences between the results of both emissions and power generation can be explained by applying relatively high starting costs in the modelling set-up comparing to other hard coal-based power plants. The Rybnik power plant is an old unit and the model does not select it favourably.

a)



b)

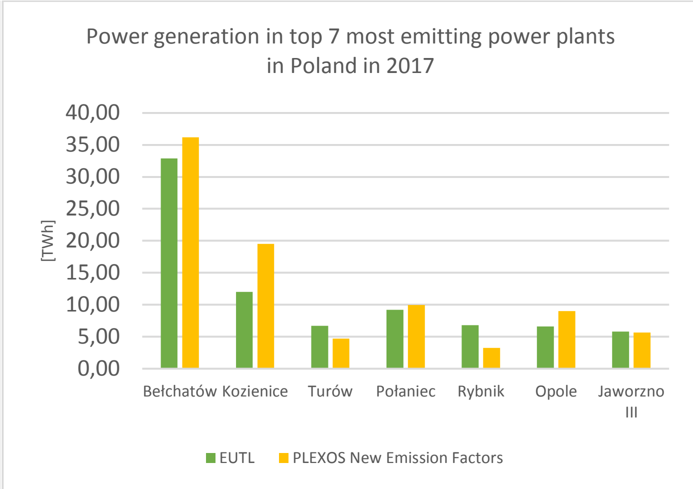


Figure 17: Comparison of power generation in top seven most polluting combustion plants in Poland in a) 2016, b) 2017, among EUTL and three PLEXOS model set-ups.

Generally, the pattern of emissions generation is a reflection of power generation. Any deviations from this behaviour should be explained by mismatches in the installed capacities, emission factors and intensity or specific definition of the unit's parameters in the modelling set-up. The last one results in different operation of the unit than it takes place in the reality. Thus, it is a recommended way to validate the model input and set-up.

3.3. Findings:

The EUTL constitutes a reliable reference database allowing to compare the verified historical emissions across the EU Member States. However, a missing division between the unit's type does not enable the direct assessment of the emissions abatement in heat and power sectors. The one prepared for this study's purpose is not free of errors due to the data inconsistency. Some of the combustion plants are considered as the condensing power plants despite of a small share of district heating functionality by one source, whereas other sources classify them already as the CHP units.

The emissions based on the fuel consumption in Eurostat should be higher than the ones obtained as the models' output. The available energy balances indicate the gross values, whereas the PLEXOS model considers the net ones. Moreover, the fuels listed in the Eurostat database are more diversified, whereas in the PLEXOS modelling set-up only the main fuels are selected. Even a small share of highly emitting fuel in the power generation can cause a significant difference in the total emissions generation, e.g. coke oven gas produces 403 kg of emissions per 1 MWh of generated electricity (Koffi et al., 2017).

Therefore, the EUTL is a robust reference database to compare the electricity-related emissions generated by the condensing power plants only of a power system model, e.g. PLEXOS. However, the Eurostat energy balances are seen as a better source to obtain the referential level of electricity-driven emissions from both the condensing power plants and CHP units.

Power system models, like the ones developed in the PLEXOS software, can underestimate or overestimate electricity generation depending on the fuel. Nevertheless, the total power generation matches the one indicated in the referential energy balances. Validation on a fuel level is useful in terms of the model's adjustment and improvements towards its more realistic operation.

Assessing the power system model's accuracy cannot be done only at the fuel level and based on its power or emissions production. The overall balance should match, i.e. installed capacity provided as the model input supposed to reflect the one installed in the reality. Electricity demand should be covered by supply. The overestimation of power generation per one fuel is quite often balanced by underestimated results of the electricity generation per another fuel. The above analysis allows to identify the prevailing model's behavior. Nevertheless, the overall model's performance should be also assessed.

4. Conclusions

This study presents a method enabling the validation of a power sector model developed in the PLEXOS software by cross-checking the accuracy of generated CO_2 emissions levels. Comparing the model's output with the reference statistics is possible for historical periods, whereas future trends should be referred to the ones given by other optimization models with the aligned input.

Among the abundance of referential sources available online, the EU ETS and Eurostat are chosen as the most relevant for this study. The first one is used as a reference list of the condensing power plants considered in the 3rd model set-up, i.e. *'EUTL stack'*. Simultaneously, the emissions results of this particular case are found as the pre-eminent among the created model set-ups. The EUTL is thus a reliable source allowing to identify the emissions generated by an individual power plant only if the names of the units are matching in both analysed model and EUTL. Applying the unified ID codes solves a problem of possible errors in the units' ascription. Comparing the emissions on a power plant level helps to identify the unit's operation. The excess emissions returned by the model and consequently, significantly lower emissions reported to the EUTL, indicates that the model does not reflect its real performance. This might be caused by either too high-power generation or applying wrong emission factors. In the considered PLEXOS model, analysing the emissions on a power plant level is possible only in the case of condensing power plants since they are defined individually, whereas the CHP units are aggregated by fuels for the particular countries.

However, the fuel consumption gathered in the energy balances prepared by Eurostat allows to estimate the national emissions from the whole power sector. Thus, the Eurostat covers the electricity-related emissions from both the condensing power plants and CHP units. Therefore, it is important to provide a clear distinction between the condensing plants and the ones working on cogeneration mode, and to define them properly by applying the relevant emission factor or efficiency. As mentioned above, the 3rd model set-up of the PLEXOS and OSeMOSYS models with the updates sets of units, demonstrates the best match of the results between the models and reference statistics.

Another component affecting the emissions results is a set of applied emission factors. Its effect can be especially seen while comparing the results of the 1st and 2nd model set-ups. It is recommended to apply the national emission factors for the fuels when it is possible. The fuel quality has got an impact on the magnitude of generated emissions. In all of the analysed cases, by using the unified emission factors in the 2nd model set-up, which are higher than in the 1st case, the emissions are explicitly boosted.

In terms of predicting future levels of CO_2 emissions, a comparison of the trends with another modelling tool is found to be relevant. This can be done only if the models are aligned to a certain degree in terms of input data to recreate as close as possible performance. For the purpose of this study, the OSeMOSYS software is chosen to confirm the range of emissions values generated by the PLEXOS models. Nevertheless, the alignment of PLEXOS and OSeMOSYS models is simplified due to the significant differences in the structure of both software. Aggregation of the power plants and grouping them by technologies in OSeMOSYS resulted in applying the average values of some parameters (e.g. variable costs), which are specified individually in the PLEXOS model. Any differences in the dispatch are caused by the incompatible demand profiles used by the models. An abundance of parameters in the PLEXOS software enables the user to recreate a real operation of a power system, whereas OSeMOSYS is a more user-friendly piece of software, even for not experienced energy system analysts, due to its simplified layout. The specificity and source of differences in the models' outcomes arise from the annual values used by the OSeMOSYS software and an hourly resolution provided by PLEXOS. A deepened analysis and improved quality of the results could be obtained by developing the OSeMOSYS model or by using another software allowing to reflect the country's power sector in details. A different structure and principle of working of the models may result in their different behavior and optimization of the power system even despite of the prior alignment. This statement can be confirmed by the last comparisons of the generated emissions per fuel across PLEXOS and OSeMOSYS model set-ups. Even though the emissions on the annual level match in the corresponding model set-ups, the share of their sources varies significantly.

The complexity of the PLEXOS model can imply a conclusion that changing the parameters only for two countries, may perturb the final results. Thus, it is recommended to analyse the whole input, update all of the countries and validate in terms of provided instructions in this study. The emissions of Germany and Poland should be checked once again after rerunning the fully updated model, due to the connections between the European countries which are also reflected in the PLEXOS model.

The obtained results confirm that the overarching objective of the study, i.e. the PLEXOS model validation, is met. Identifying the relevant reference statistics give credibility to the validation process. The objects affecting the CO_2 modelling are identified what enables to set the model up correctly. The emissions returned by the *'EUTL stack'* model set-ups differ only by 3.6-3.9% in the case of Germany, and 1.2-4.7% for Poland between 2016-2017, comparing to the ones calculated from the Eurostat energy balances.

However, the modelling software are not deprived of the limitations. Despite of the detailed data input, the model's behaviour will not reflect the real power system in all of the dimensions. The made assumptions which are user-dependant and the model's structure, have a direct impact on the results. Moreover, the energy sector is affected by the social and geopolitical factors. The energy system modelling should only indicate a direction of possible changes.

5. Suggested future work

The presented method allowing to validate a power system model in terms of generated levels of CO_2 emissions, is assumed to be only one of a plethora of different solutions. A few more ideas enabling the improvement of the proposed procedure or to investigate the newly raised topics while performing this study, are listed below:

- Applying the created method for the whole PLEXOS model (i.e. all of the countries), to minimize the impact of changes in one country to another due to the connections between them;

- Creating one input database which can be automatically adjusted and implemented to the model;
- Applying the unified ID codes for the power plants in the input database in order to identify them easily in the international registries, e.g. in the EU ETS;
- Regrouping some of the categories in the output to compare them easily, e.g. generating the results separately for biomass and waste;
- Analysing the heating sector on its own with a special emphasis put on the emissions generated by the CHP units and developing the model by other energy sub-sectors like a residential one or transport;
- Further developing the available OSeMOSYS models in order to improve the results and move towards the PLEXOS ones by e.g. implementing all of the combustion stations individually, making a distinction between hard coal and lignite, etc.;
- Comparing the emissions results obtained in another, equally complex power sector model as PLEXOS, different than OSeMOSYS, by providing a relevant alignment;
- Investigating other sources and databases which could become the referential sources to validate the magnitude of CO_2 emissions generated by the power sector models;
- Modelling other emissions than CO_2, e.g. NOx or SO_2 and correspondingly preparing a relevant analysis for their validation.

Bibliography

BCG (2018) *Klimapfade für Deutschland*. Available at: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2018/Januar/Klimapfade_fuer_Deutschland_BDI-Studie_/Klimapfade-fuer-Deutschland-BDI-Studie-12-01-2018.pdf (Accessed: 5 June 2019).

BMU (2010) *The Federal Government's energy concept of 2010 and the transformation of the energy system of 2011*. Berlin: Federal Ministry of Economics and Technology (BMWi), p. 37. Available at: https://cleanenergyaction.files.wordpress.com/2012/10/german-federal-governments-energy-concept1.pdf (Accessed: 5 June 2019).

Bundesnetzagentur (2019) *List of Power Plants*. Available at: https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/SecurityOfSupply/GeneratingCapacity/PowerPlantList/PubliPowerPlantList_node.html (Accessed: 5 June 2019).

Business Insider (2018) *Na świecie trwa boom na morską energetykę wiatrową. Polska na razie w poczekalni*, *Business Insider*. Available at: //businessinsider.com.pl/finanse/powstana-morskie-elektrownie-wiatrowe-w-polsce/lt06409 (Accessed: 4 June 2019).

CDM (2019) *CDM: About CDM*. Available at: https://cdm.unfccc.int/about/index.html (Accessed: 5 June 2019).

D. I. W. (2007) *The Spatial Optimization Model of the Electricity Sector "ELMOD"*. Available at: https://www.diw.de/de/diw_01.c.528493.de/forschung_beratung/nachhaltigkeit/umwelt/verkehr/energie/modelle/elmod.html#ELMOD-DE (Accessed: 5 June 2019).

DEHSt (2013) *Reforming the EU ETS with regard to the EU´s medium- and long-term climate targets*. Berlin: German Emissions Trading Authority (DEHSt), p. 26. Available at: https://www.dehst.de/SharedDocs/downloads/EN/emissions-trading/zielpapier.pdf?__blob=publicationFile&v=2 (Accessed: 5 June 2019).

EEA (2018a) *Reported data on large combustion plants covered by the Industrial Emissions Directive (2010/75/EU)*, *European Environment Agency*. Available at: https://www.eea.europa.eu/data-and-maps/data/lcp-5 (Accessed: 5 June 2019).

EEA (2018b) *Trends and projections in the EU ETS in 2018*, *European Environment Agency*. Available at: https://www.eea.europa.eu/publications/trends-and-projections-in-the (Accessed: 5 June 2019).

EEA (2019) *European Environment Agency's home page*, *European Environment Agency*. Available at: https://www.eea.europa.eu (Accessed: 5 June 2019).

Egenter, S. (2019) *German commission proposes coal exit by 2038*, *Clean Energy Wire*. Available at: https://www.cleanenergywire.org/factsheets/german-commission-proposes-coal-exit-2038 (Accessed: 5 June 2019).

Energy Exemplar (2019) 'PLEXOS® Simulation Software', *Energy Exemplar*. Available at: https://energyexemplar.com/products/plexos-simulation-software/ (Accessed: 5 June 2019).

Energy Innovation (2018) *Poland's Path to Tackling Climate Change: 40% fewer Emissions, $26 billion Annual Savings by 2050*, *Energy Innovation: Policy and Technology*. Available at:

https://energyinnovation.org/article/polands-coal-addiction-changing-its-energy-plan-could-cut-emissions-40-save-19-billion-annually/ (Accessed: 5 June 2019).

Energy Innovation LLC (2019) *Poland. Energy Policy Solutions*. Available at: https://poland.energypolicy.solutions/ (Accessed: 5 June 2019).

ENTSO-E (2019) *ENTSO-E Transparency Platform*. Available at: https://www.entsoe.eu/data/ (Accessed: 5 June 2019).

European Commission (2016a) *EU Emissions Trading System (EU ETS)*, *Climate Action - European Commission*. Available at: https://ec.europa.eu/clima/policies/ets_en (Accessed: 5 June 2019).

European Commission (2016c) *NER 300 programme*, *Climate Action - European Commission*. Available at: https://ec.europa.eu/clima/policies/innovation-fund/ner300_en (Accessed: 5 June 2019).

European Commission (2018b) *Report from the Commission to the European Parliament and the Council. Report on functioning of the European carbon market*. Brussels. Available at: https://ec.europa.eu/clima/sites/clima/files/ets/docs/com_2018_842_final_en.pdf (Accessed: 5 June 2019).

European Commission (2016b) *Union Registry*, *Climate Action - European Commission*. Available at: https://ec.europa.eu/clima/policies/ets/registry_en (Accessed: 5 June 2019).

European Commission (2010) *Europe 2020. A strategy for smart, sustainable and inclusive growth*. Brussels: COM. Available at: europeanhttp://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20BARROSO%20%20%20007%20-%20Europe%202020%20-%20EN%20version.pdf (Accessed: 5 June 2019).

European Commission (2018a) *In-depth analysis in support of the commission communication. A Clean Planet for all. A European long-term vision for a prosperous, modern, competitive and climate neutral economy.* Brussels. Available at: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf (Accessed: 4 June 2019).

European Commission (2019) *EU Emissions Trading System (ETS) data viewer*, *European Environment Agency*. Available at: https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1 (Accessed: 5 June 2019).

European Union (2016) *The EU Emissions Trading System (EU ETS)*. ML-06-16-080-EN-N. Available at: https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf (Accessed: 5 June 2019).

Eurostat (2019) *Energy balances*. Available at: https://ec.europa.eu/eurostat/web/energy/data/energy-balances (Accessed: 5 June 2019).

EUTL (2017) *EUROPA - Environment - Kyoto Protocol - European Union Transaction Log*. Available at: http://ec.europa.eu/environment/ets/napYearInformation.do?napId=19762&periodYear=2017&registryCode=SE&%20action=periodYear&installationId=&languageCode=en&periodCode=2 (Accessed: 5 June 2019).

IEA (2017) *CO2 Emissions from Fuel Combustion 2017 - Highlights*. OECD/IEA, p. 162. Available at: https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustion Highlights2017.pdf (Accessed: 5 June 2019).

Itkonen, A.-K. and Rietdorf, L. (2018) *European Commission - PRESS RELEASES - Press release - The Commission calls for a climate neutral Europe by 2050**. Available at: http://europa.eu/rapid/press-release_IP-18-6543_en.htm (Accessed: 5 June 2019).

Jurich, K. (2016) 'CO2 Emission Factors for Fossil Fuels', *German Environment Agency (UBA)*, p. 48.

KOBIZE (2016) *Wartości opałowe (WO) i wskaźniki emisji CO2 (WE) w roku 2014 do raportowania w ramach Systemu Handlu Uprawnieniami do Emisji za rok 2017*. Warsaw: IOŚ-PIB. Available at: http://www.kobize.pl/uploads/materialy/materialy_do_pobrania/monitorowanie_raportowanie_weryfikacja_emisji_w_eu_ets/WO_i_WE_do_stosowania_w_SHE_2018.pdf (Accessed: 5 June 2019).

KOBIZE (2018) *Poland's National Inventory Report 2018. Greenhouse Gas Inventory for 1988-2016*. Warsaw: IOŚ-PIB. Available at: http://www.kobize.pl/uploads/materialy/materialy_do_pobrania/krajowa_inwentaryzacja_emisji/NIR_2018_POL.pdf (Accessed: 5 June 2019).

Koffi, B., Cerutti, A., Duerr, M., Iancu, A., Kona, A., Janssens-Maenhout, G. B., (2017) *CoM Default Emission Factors for the Member States of the European Union*. Joint Research Centre (JRC). Available at: https://cidportal.jrc.ec.europa.eu/ftp/jrc-opendata/COM-EF/dataset/comw/JRC-CoM-EF-CoMW-EF-2017.pdf (Accessed: 5 June 2019).

KTH-dESA (2018b) *OSeMOSYS*, *OSeMOSYS*. Available at: http://www.osemosys.org/ (Accessed: 5 June 2019).

KTH-dESA (2018c) *Structure of OSeMOSYS — OSeMOSYS 0.0.1 documentation*. Available at: https://osemosys.readthedocs.io/en/latest/manual/Structure%20of%20OSeMOSYS.html (Accessed: 5 June 2019).

KTH-dESA (2018a) *Welcome to the OSeMOSYS' documentation! — OSeMOSYS 0.0.1 documentation*. Available at: https://osemosys.readthedocs.io/en/latest/ (Accessed: 5 June 2019).

Ministerstwo Energii (2018) *Polityka Energetyczna Polski do 2040 roku (PEP2040)*. Warszawa. Available at: https://www.gov.pl/documents/33372/436746/PEP2040_projekt_v12_2018-11-23.pdf/ee3374f4-10c3-5ad8-1843-f58dae119936 (Accessed: 5 June 2019).

Pfenninger, S., Hawkes, A. and Keirstea, J. (2014) 'Energy systems modeling for twenty-first century energy challenges', *Renewable and Sustainable Energy Reviews*, 33, pp. 74–86. doi: 10.1016/j.rser.2014.02.003.

PLEXOS (2011) *PLEXOS Guide*. Fortum.

PSE (2019) *Raporty za rok 2018 - PSE*. Available at: https://www.pse.pl/dane-systemowe/funkcjonowanie-rb/raporty-roczne-z-funkcjonowania-kse-za-rok/raporty-za-rok-2018 (Accessed: 5 June 2019).

Rada Ministrów (2009) *Polityka energetyczna Polski do 2030 roku*. Warszawa: Ministerstwo Gospodarki. Available at:

https://www.gov.pl/documents/33372/436746/DE_Polityka_energetyczna_ost_2030.pdf/78b689ec-62ec-af88-b0d7-decf95abdb70 (Accessed: 5 June 2019).

REEEM (2019) ‘REEEM – Energy Systems Modelling Project’. Available at: http://www.reeem.org/ (Accessed: 5 June 2019).

Russell, R., Wettengel, J. (2017) *The main stories of Germany’s Energiewende*, *Clean Energy Wire*. Available at: https://www.cleanenergywire.org/factsheets/main-stories-germanys-energiewende (Accessed: 5 June 2019).

Schmid, E., Knopf, B. and Bauer, N. (2012) ‘Remind-D: A Hybrid Energy-Economy Model of Germany’, *SSRN Electronic Journal*. doi: 10.2139/ssrn.2026443.

Suwała, W., Wyrwa, A. and Pluta, M. (2017) ‘Near future of Polish energy system – COP21 and BAT conclusions’, *E3S Web of Conferences*, 14, p. 01001. doi: 10.1051/e3sconf/20171401001.

United Nations (1998) *Kyoto Protocol to the United Nations Framework convention on climate change*. Kyoto. Available at: https://unfccc.int/sites/default/files/kpeng.pdf (Accessed: 5 June 2019).

Appendix

Appendix A – European Strategy and Energy Policies

European Strategy

The following section presents the targets and measures of climate change mitigation set by the EU.

EU Long-term goals

By creating the *Clean Planet for all*, long-term plan, the EU moves towards a climate neutral economy by 2050. It is not only a general overview and set of targets, but an actual plan with different ideas available for all of the Member States. It aims to provide a variety of solutions for the countries on a different development stage. At the same time, it seeks to continue a sustainable economic growth and to diminish the wealth inequality on an international level. Changes in economy and society are its inherent part. Arising environmental challenges, like food competition with increased biomass usage for the energy-generating purposes, will be met by creating *synergies*. The last one can be understood that by implementing renewables, air quality will be improved what has got a positive impact on human health and meeting the decarbonization targets. The EU, as a pioneer, seeks to inspire other nations to contribute to the climate change mitigation. The plan assumes that the main goal is feasible to be reached due to the currently used technologies, as well as those close to deployment. Seven strategies constitute a core of the project:

- Improved energy efficiency including zero emission buildings;
- Higher share of renewables in the final energy generation balance;
- Decarbonisation in the mobility system by implementing digitalisation, alternative fuels and smart infrastructure;
- Competitive industry;
- Improved infrastructure and any kind of connections (electrical, transport, etc.);
- Natural absorption of carbon by bio-systems;
- Developing carbon capture and storage (CCS) technology for the remaining emissions (Itkonen et al., 2018).

Above roadmaps should be merged and developed in order to reach the net-zero GHG economy. The EU Member States have got a freedom of choice with regards to where they want to particularly focus on. More favourable situation and geographical location of one country will propel an implementation of renewables, whereas another nation will not have enough resources nor conditions to make similar investments (European Commission, 2018a).

EU ETS

The European Emissions Trading System (European Union, 2016), is an important tool aiming to combat climate change caused by excessive generation of GHG as a result of human activity. It operates in 31 countries (includes 28 EU Member States, Iceland, Norway, Lichtenstein); and constitutes the biggest emission volume-control system of this kind. The accounted installations, power plants and industrial units, are listed in the Union Registry database. Currently, it covers around 11,000 power stations and aviation activities, accounting for 45% of the GHG generated in the EU. The list of all of the activities included in the EU ETS is gathered in Table 1 below. The category *No 20*. deserves a special attention since *Combustion of fuels* is mainly applied to power plants where the oxidation of fuels takes place.

Activity type code	Activity
10	Aviation
20	Combustion of fuels
21	Refining of mineral oil
22	Production of coke
23	Metal ore roasting or sintering
24	Production of pig iron or steel
25	Production or processing of ferrous metals
26	Production of primary aluminium
27	Production of secondary aluminium
28	Production or processing of non-ferrous metals
29	Production of cement clinker
30	Production of lime, or calcination of dolomite/magnesite
31	Manufacture of glass
32	Manufacture of ceramics
33	Manufacture of mineral wool
34	Production or processing of gypsum or plasterboard
35	Production of pulp
36	Production of paper or cardboard
37	Production of carbon black
38	Production of nitric acid
39	Production of adipic acid
40	Production of glyoxal and glyoxylic acid
41	Production of ammonia
42	Production of bulk chemicals
43	Production of hydrogen and synthesis gas
44	Production of soda ash and sodium bicarbonate
45	Capture of greenhouse gases under Directive 2009/31/EC
46	Transport of greenhouse gases under Directive 2009/31/EC
47	Storage of greenhouse gases under Directive 2009/31/EC
99	Other activity opted-in pursuant to Article 24 of Directive 2003/87/EC
20-99	All stationary installations
21-99	All industrial installations

Table 1: EUTL Activity type (European Commission, 2019).

A carbon price is set which results in trading the allowances to emit emissions by the registered units. This applies particularly to CO_2, which is the main component of GHG, but also to nitrous oxide (N_2O) and perfluorocarbons (PFC) generated in some industrial processes. A total limit of emissions which might be produced is set for the whole EU called a *cap*. The main idea is to reduce the cap by 1.74% per year, comparing to the quantity of allowances issued annually in 2008-2012. In that way, the emission level in 2020 should be 21% lower than in 2005 when the system arose (European

Commission, 2018b). At the same time, the companies buy or sell the surplus allowances, saved due to their judicious utilisation in the previous years, which concerns a *trade* part.

Constant monintoring of the emission levels is needed to check the impact of taken actions and to improve the trading system. The anual emissions along with the used allowances, are reported by the national authorities and forwarded to the European Commission by the end of April. The companies which emit more than the owned EUA, must pay a penalty. In 2013, the penalty price was around 100 EUR per extra emitted tonne of CO_2 or equivalent amount of N_2O or PFCs. The revenue gained from the allowances' trading is partially used to support the funding programme *NER300* (European Commission, 2016c). The latter focuses on an introduction of large-scale, low-carbon projects, i.e. carbon capture and storage (CCS), and innovative renevable energy technologies (European Union, 2016).

The allowances might be issued by the countries as a part of the Clean Development Mechanism (CDM) and Joint Implementation (JI), (CDM, 2019), accepted by the Kyoto Protocol (United Nations, 1998). These projects gather the particular activities resulting in additional reduction of emissions on a national level. By creating the incentives for a sustainable development, Certified Emission Reduction (CER) credits and Emission Reduction Units (ERUs) are obtained accordingly. They can be further exchanged for the EUA, since one credit is equivalent to one tonne of CO_2 emissions removed from the atmosphere in terms of the emissions reduction project. International credits are predicted to be in use by the end of EU ETS Phase 3, i.e. by the end of 2020 (CDM, 2019).

The EU ETS constantly embraces changes in order to provide the best possible solutions to face the emissions problem. Figure 1 shows the system development in four phases. Every phase is adequate to one trading period. The action plan and the carbon emission reduction targets are available by 2030.

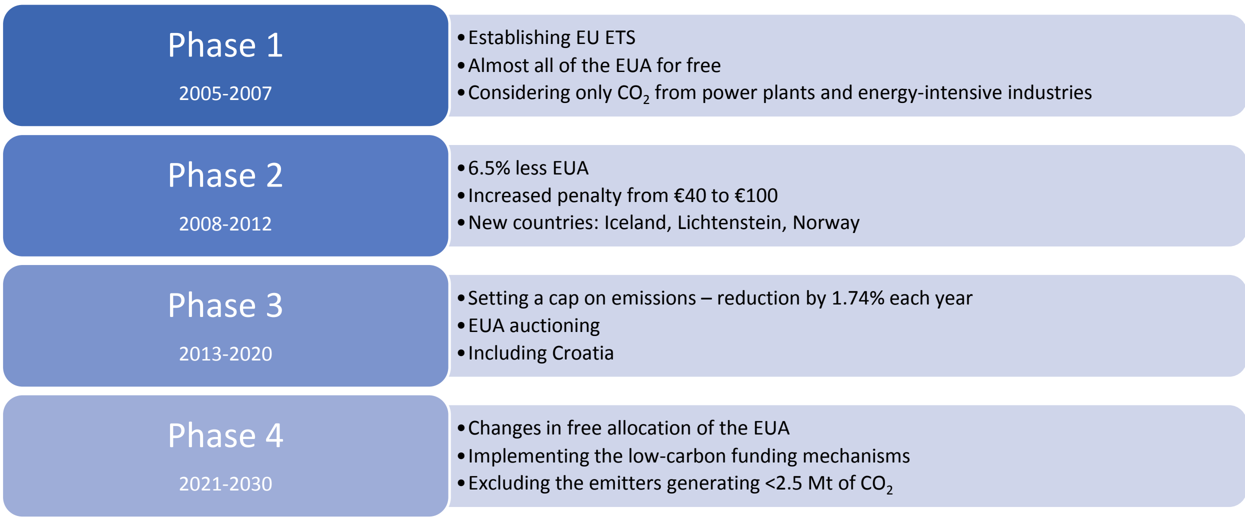


Figure 1: Four phases of EU ETS (European Union, 2016).

A part of the allowances is distributed for free. So far, the free allowances were distributed as a distinction to 10% of the most efficient installations. The allocation is transparent, known in advance and based on the benchmarking regulation. During the Phase 4, this kind of allowances will be given for the companies which display a high risk of relocation outside of the EU. This situation must be avoided to reduce *a carbon leakage* effect. The industries with the highest probability of moving their production to other countries will get 100% of free EUA. Others will benefit from 30% free allowances by 2026 and their gradual phase out will be finished by 2030. The allocation will depend on the used technology and its development, as well as on the energy production level (European Commission, 2018b).

The European Union Transaction Log (EUTL), (EUTL, 2017), is a database run by the European Commission where all of the transactions concerning the EUA issues within the trading system are recorded. The level of verified, historical emissions, total or freely allocated allowances and the number of considered units can be displayed online in a graphical form for all of the countries belonging to the system between the timeframe 2005-2017 (European Commission, 2019). Figure 2 shows an example of the verified emissions and accompanying allowances between 2010-2017 in Germany and Poland, registered in the EUTL and covered by the activity *No 20. Combustion of fuels.*

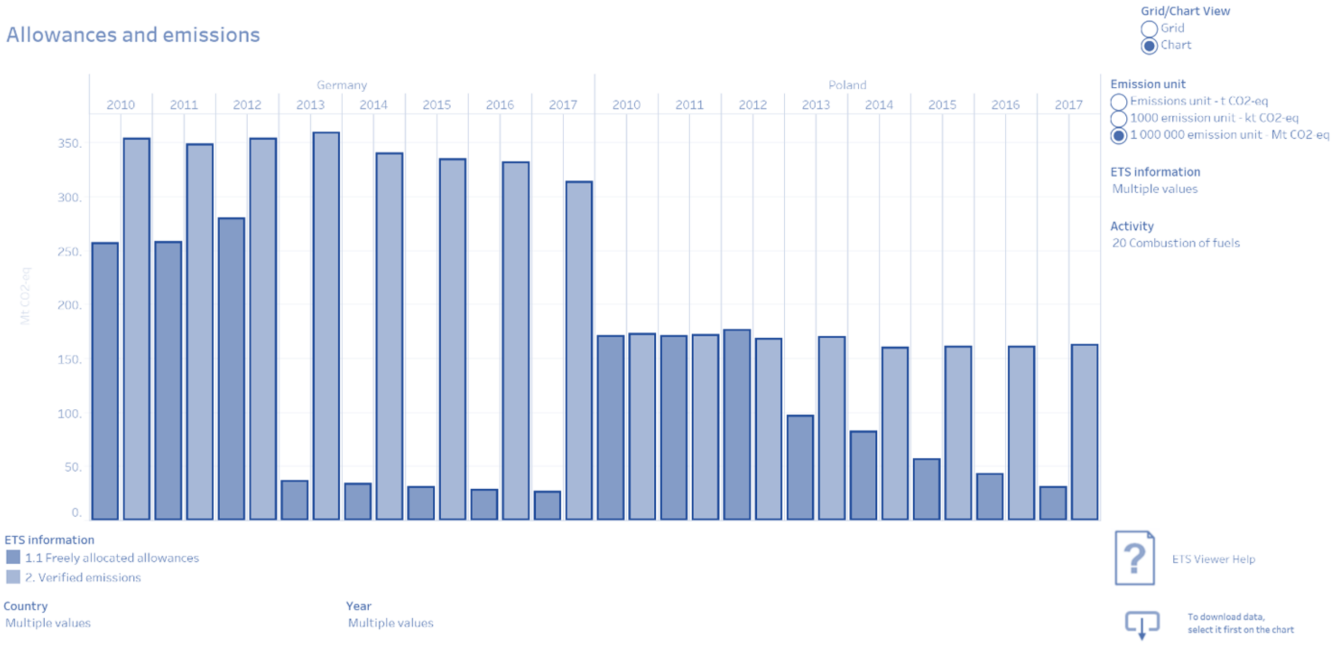


Figure 2: Allowances and emissions covered by the activity 'No 20. Combustion of fuels' between 2010-2017 in Germany and Poland (EUTL, 2017).

It was noticed, that the total amount of emissions in 2017 generated by the installations gathered in the EUTL, was higher by 0.18% than in the previous year (1754 Mt_{CO2} vs. 1751 Mt_{CO2} in 2016). However, it can be explained by a relatively high GDP growth at the level of 2.4% in that year. The overall performance improved on a power sector side, since it mainly contributes to the emissions generation but constantly reduces its level (European Commission, 2018b).

Due to the excessive number of allowances on the market, the ETS had to undergo a reform in 2015. The Market Stability Reserve (MSR) was created to reduce the oversupply of EUA and to achieve the desired effect of reduced emissions. The mechanism started its operation in January 2019. In the first eight months of 2019, the auction volume will be reduced by 40% comparing to the amount of allowances available in the previous year. The allowances are placed to the reserve by the end of 2023. However, they can be released earlier when needed (European Commission, 2018b).

Nevertheless, there are yearly limits set on each Member State regarding the non-ETS sector according to the decision 2013/634/EU made by the European Commission. Effort Sharing Decisions (ESD) is a mean helping to decrease the GHG which occur beyond the ETS by setting emission reduction targets (KOBIZE, 2018).

Energy Policies

Germany

In September 2010, the German Federal Government released the *Energy Concept* (BMU, 2010) – a long-term plan of the energy system transformation. It contains the list of measures enabling the country to achieve the set targets. One of the most important goals is the gradual 80% GHG reduction by 2050 compared to 1990 level, which is depicted in Figure 3 below. It can be done by increasing the share of renewables up to 60% in the final energy consumption by 2050 – a timeline presented in Figure 4.

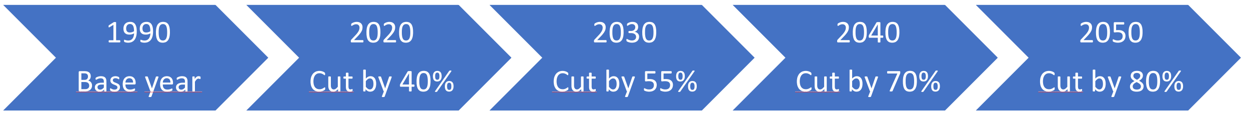


Figure 3: GHG reduction targets by 2050 in Germany (own elaboration based on (BMU, 2010)).

Figure 4: Share of renewables (RE) in the gross electricity consumption by 2050 in Germany (own elaboration based on (BMU, 2010)).

Electricity is expected to lead in the low-carbon economy, and the whole energy system transition is called the *Energiewende* (Russell et al., 2017). The analyses show that it can almost totally eliminate CO_2 emissions by 2050 and offer the opportunity to partially replace fossil fuels in transport and heating sectors. The net electricity consumption is predicted to slightly increase from 515 TWh in 2015 to 537 TWh in 2050. These data already consider a bigger introduction of electric vehicles (EV) and heat pumps into the electricity market (BCG, 2018). However, the target of implementing one million of EV on the German roads by 2020 seems to be impossible to reach (Russell et al., 2017). Considering the timeframe, the growth remains relatively small thanks to the improvements in the energy efficiency (BMU, 2010).

The electricity demand is predicted to be covered by renewables by 80% by 2050 due to more than 2.5 times larger implementation of wind onshore and offshore, as well as photovoltaics compared to 2015. The offshore wind capacity is planned to be boosted up to 25 GW by 2030. Bioenergy is predicted to gain more attention by its sustainable usage. At the same time, the market will remain competitive. Due to higher implementation of renewables, energy storage (mainly electricity) will be more promoted (BMU, 2010).

Hard coal and lignite-fired power plants are predicted to be in operation as long as they are economically profitable, and they will cover around 18 GW of generating capacity by 2018. It is assumed that 88 GW of a marginal capacity saved for security reasons should be maintained by 2050. This will be covered by conventional power plants with a net addition of gas-fired power plants with a capacity of 33 GW. A partial coal phase-out is in an ongoing process and will last until 2038. Such a decision was taken in June 2018 by the German government due to significant amount of emissions generated by the fossil fuel-based units (Russell et al., 2017). According to the EUTL, the verified emissions accounted for category *20. Combustion of fuels* were the highest in Germany among the system Parties in 2017 (EEA, 2018b). However, the total emissions are taken into account. Different classification could be obtained by looking at the values per capita or considering other factors, like a size of the industry sector. Nuclear phase-out is expected to be accomplished by the end of 2022. This decision was followed by the nuclear meltown accident at Fukushima in 2011 (BMU, 2010).

The *Grid Development Plan* by 2030 (BCG, 2018) assumes that the new international grid connections should be created across the Europe in order to minimize the cost and emissions generation by reducing the power shortages. It will prevent the system from running highly emitting fossil fuel-based generation units (BCG, 2018). This is also a crucial step to implement successfully the significant number of renewable sources. Rapid growth of wind capacity must be followed by a stable grid development being able to receive a significant amount of power (Russell et al., 2017).

According to the *Climate Paths for Germany* study (BCG, 2018), all of the above goals are feasible but too ambitious to be met by 2050. Bigger investments and higher commitments of the policy makers are missing. A realistic GHG reduction is expected to be at 61% comparing to 1990 level, what is presented in Figure 5 below.

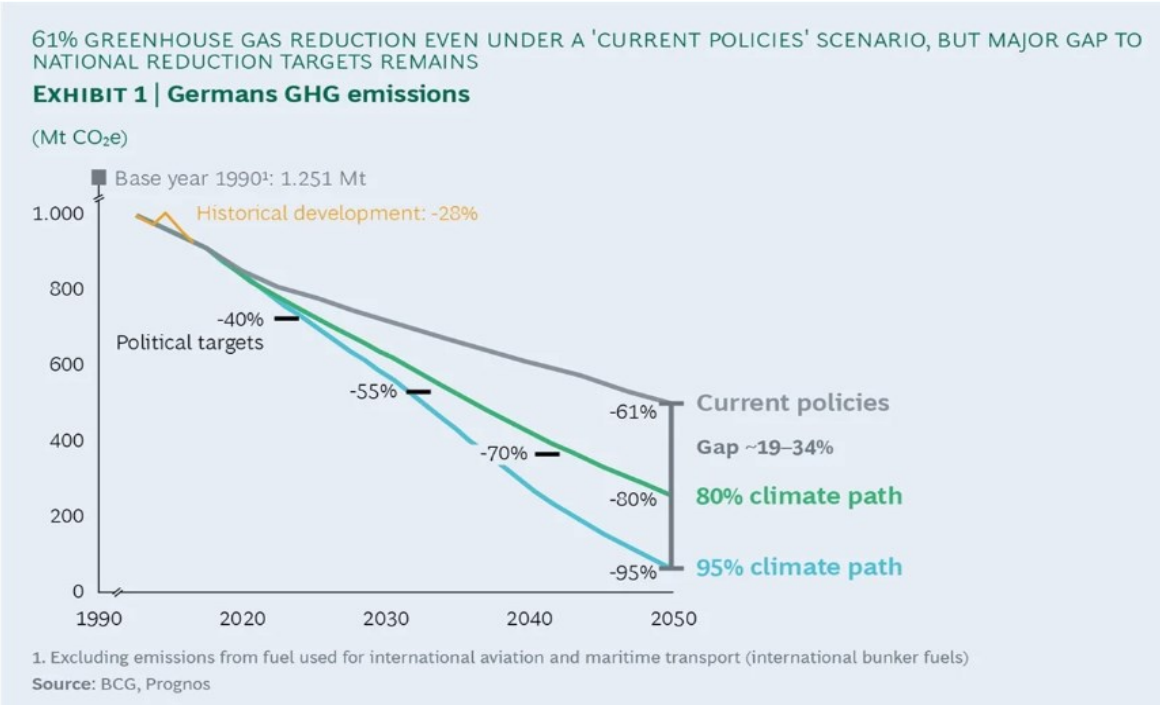


Figure5: A comparison of the GHG reduction trends in Germany by 2050 according to several possible scenarios (BCG, 2018).

Poland

Long-term strategies of the Polish energy sector are presented by the Ministry of Energy. The first project was released in 2009 (Rada Ministrów, 2009), and it was followed by releasing the Europe 2020 Strategy (European Commission, 2010). However, it only underlines the most important directions of the energy policy, like energy efficiency improvement or providing energy security, without stating the needed measures (Rada Ministrów, 2009).

The most recent project is the *Energy Policy by 2040 in Poland (PEP2040)*, released on 23rd November 2018 (Ministerstwo Energii, 2018). It indicates, among others, the implementation of the first nuclear power plant in the country. It should start its operation in 2033 with 1.5 GW installed capacity, which will be followed by adding five new units by 2043 with a total power of 9 GW. In reality, this scenario is seen as an optimistic one because even the plant location is not chosen yet and the new nuclear unit is only planned, not committed.

Moreover, in order to diversify the Polish energy mix, geothermal energy is predicted to be an important heating source. The largest resources are located in the western part of the country but are not exploited yet. Due to high costs of the drilling investigations, an explicit goal is not clear but the predicted developed is expected to occur between 2020-2050.

The policy does not assume a significant growth of onshore wind capacity; its expansion was more beneficial until 2007 with the help of green certificates. However, due to a development of the grid in the northern part of Poland, offshore wind deserves attention and the first farm will be constructed in 2025. It is estimated that by 2035 there will be a few new units with a total capacity of 10 GW (Business Insider, 2018).

Changes in the energy mix are urgent since Poland is among five the most emission producing countries belonging to the EU ETS (European Environmental Agency, 2018). The CO_2 emissions accounted for around 80% of GHG generated in Poland in 2016 (KOBIZE, 2018). More than 92% of CO_2 is derived from the fuel combustion and the largest share is attributed to the Energy Industries (52.37%), which is presented in Figure 6.

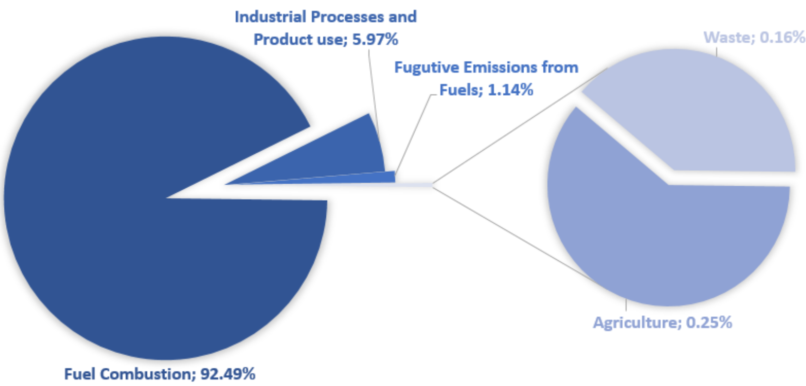


Figure 6: CO_2 sources in Poland in 2016 (own elaboration based on (KOBIZE, 2018)).

Poland has obliged to reduce the GHG emissions by 40% by 2050 compared to 2005 level. Percentage wise, this is half the size of the German target. However, it is still challenging due to the current high reliance on fossil fuel-based energy generation units. Coal is the only abundant source straightening the Polish energy security. Nevertheless, the lack of investments in the mining sector results in leaving behind its cost-effectiveness comparing to the neighbouring countries using modern technologies. A pattern of importing natural gas from Russia has started to be visible also on a coal side, loosing Polish independency from imported resources (Energy Innovation, 2018).

Appendix B – PLEXOS model

The section below is not a user guidance nor a manual on its own. All the information is supported by the references where it is stated. A part of the description is based on own experience and knowledge obtained during a PLEXOS training and model's validation.

Modelling

Each of a PLEXOS model contains three main components:

a) *Objects*, which are the fundamental building blocks and represent, e.g. the generators (single or aggregated power plants), fuels, emissions, companies, etc.;

b) *Memberships* indicating the relations between the *objects*, like CO_2 emissions generated by a specific power plant;

c) *Properties* giving more information about the *object* (e.g. for a particular power plant), including its capacity, heat rate, start cost, max ramp up, etc.

The *objects* are grouped in the thematic *categories*. Different blocks/turbines/engines of one coal-fired power plant or even individually implemented coal-based power plants available in one *region*, belong to one *category* (due to the same fuel). The *categories* help to organize the model, especially in the case of many different units, like all of the power plants propelled by different fuels and operated in one country.

However, all of the power plants, regardless of their main fuel, belong to one *class*, which can be called 'Generators'. The *classes* stand for more general and bigger aggregations, whereas the *categories* gather the objects with some common features. Different fuels – modelled as single *objects*, are also in one class. The CO_2, NOx, SO_2 emissions are three different *objects* but collected in one *class* called generally 'Emissions'.

By assigning one *object* to another, for example indicating what kind of fuel is burnt in a power plant, a *membership* is created. At the same time, the fuel is assigned to the power plant on a *collection* basis. Choosing the *collection* of this specific power plant - *Generator.Fuels* (note the notation with a dot for the *collection*), the assigned fuel will be displayed. The *Membership* always involves two *objects*:

- A *parent object* (in the example above it's the *Generator*);
- A *child object* (in the example above it's the *Fuel*); (PLEXOS, 2011).

A graph with an example of the PLEXOS model's structure and components can be seen in Figure 1 below.

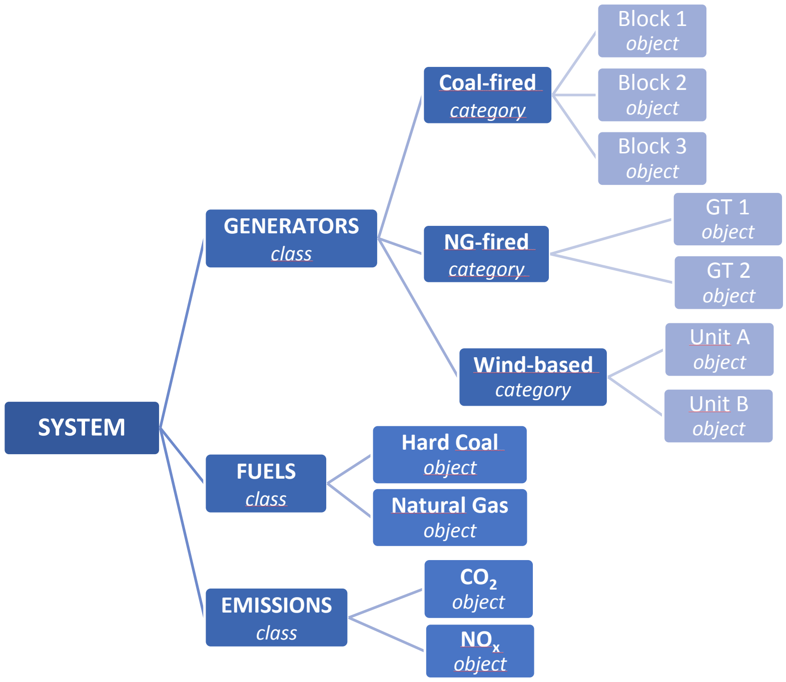


Figure 1: Structure of the components in a PLEXOS model (own elaboration).

Due to the software's complexity, PLEXOS offers a wide variety of options allowing to capture a vulnerability of the energy systems. The list of available *properties* for each *object* is extensive, whereas a possibility to create *memberships* between the *objects* enables the users to control the impact of one component to another. This constitutes a base of the well-developed optimization algorithm which chooses the best option after a careful consideration of the whole available input.

A good example is an optimization of a natural gas-fired thermal unit over a coal one. By providing the data with starting fuel costs and produced emissions levels defined by a wide set of parameters, it is more likely that PLEXOS will implement more desirable natural gas-based installations than other power system modelling software, for instance EMPS, could do in the same situation.

Simulations

The simulation engine offers four types of algorithm according to the required analysis:

a) *Long Term Plan (LT)* – suitable for long-term planning, up to 50 years, with a step size specified by the user, e.g. presenting the solution for 50 years in 5 steps of 10 years. It provides the optimal combination of the generators already in use and proposes the new investments. The LT considers also transmission upgrades and retirements. The expansion algorithm can be chosen by the user: the *linear* one usually offers a faster computation time, whereas the *integer* algorithm is more precise, usually takes longer time and may result in not finding an optimal solution. Another way to reduce the computation time is to choose a proper type of *Chronology* type among the available ones:

   - *Partial* – the most suitable option for the relatively extensive models, it represents all the constraints but simultaneously losses the chronology of the unit's commitment. It is especially recommended to choose in the settings a *monthly* Load Duration Curve (LDC), i.e. to provide 12 blocks in each LDC (each block represents one month during the year). This procedure is called a *slicing method* which gives the good results of the peak periods and indicates a general trend of the generation;

- *Fitted* – a good option for the smaller models since it is a time-consuming method. However, it shows an accurate representation of the LDC with a preserved chronology;
- *Sampled* – gives an opportunity to model only a chosen time period, e.g. one week. Each day is divided into 24 periods; thus, it results in a relatively big number of simulated periods by increasing the sample even by one day.

b) *Projected Assessment of System Adequacy (PASA)* – simulation phase suitable for a time horizon up to 10 years. It helps to determine the share of generation capacity between the *regions* (usually defined as countries for the continental models). Thus, it assures that demand is met by enough generation. In the most important settings there is, among other, a resolution time on an interval, daily or weekly level. By choosing the transmission granularity, i.e. regional or zonal one, the adequate capacity reserves are presented.

c) *Medium Term Schedule (MT)* – a compelling option for the analysts interested in detecting the changes and trends in the generation or hydro storage management between the consecutive months throughout a year. The MT can be run on a daily, weekly or monthly resolution and it bases on the LDC. It considers both the generation and transmission systems, as well as the complexity of the unit's commitment. The long-term simulations for several years are possible by skipping the Short Term Schedule (ST), described below, which results in much more detailed reports; thus, longer computation time. However, due to the integrity of all of the algorithms, the results are consistent by passing the MT results to ST schedule, if the latter is chosen. In the MT Schedule, like in the LT one, the chronology type is based on the LDC (price duration curves are possible as well) for the partial and fitted methods to model the *Horizon*. Dividing the time period into blocks results in an increased number of the simulation periods, for example 12 blocks with weekly LDC means 624 simulation periods (12 months, 4 weeks each, 52 weeks in a year).

d) *Short Term Schedule (ST)* – returns the most detailed and chronological reports with a full profile of features on a generator level. It is based on the mixed-integer programming. The corresponding time resolution varies from a few minutes up to one week. The ST simulation phase is widely used for the purposes of market simulations, optimal bidding or ancillary service optimisation (PLEXOS, 2011).

Skipping one of the algorithms mentioned above, results in the same order of their execution and computation since the results of one step are forwarded to the next one. PLEXOS provides a full integration of the simulation phases and the computation order is presented in Figure 2 below.

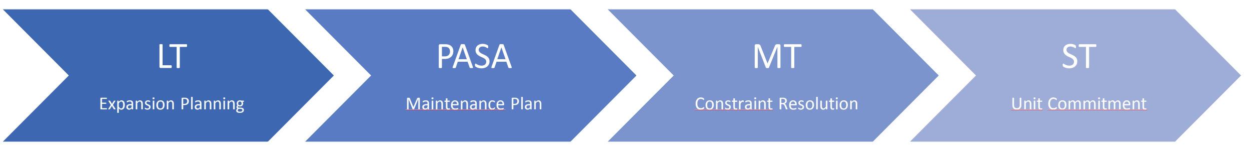


Figure 2: Computation order in PLEXOS (own elaboration based on (PLEXOS, 2011)).

Figure 3 represents a basic tree available in the *Simulation* tab in a PLEXOS model. Looking at it from the top, the set-up contains the *Models* object with its specifications, i.e. optional scenarios (added by first creating a new category called 'Scenarios' and then adding different versions of the model), and the run specifications: a set *Horizon*, basic *Report*, simulation phases (LT, PASA, MT, ST) and additional settings. The models with the same *Horizon* and *Report* are merged into the *Projects* object having the results into one solution file. Running the *Project* is a user-friendly way to compare the output of different models at the same time. Otherwise, a separate execution of each model is needed what can be further apposed in the view settings.

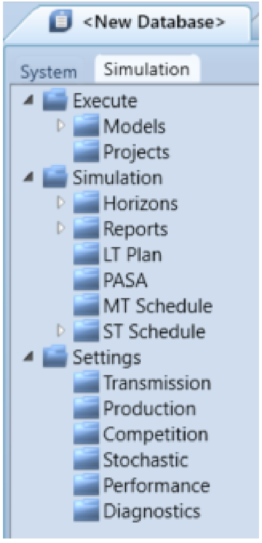


Figure 3: Structure of a tree in the PLEXOS Simulation tab

Horizon specifies the timeframe for the model; thus, it is closely dependant on a simulation phase. By running a simulation only for one year, it is important to change the step size for LT and MT accordingly. *Planning Horizon* is used for the LT and MT simulations. It contains the start date and the number of periods, e.g. 30 days. While running the ST schedule, *Chronological Phase* of the *Horizon* must be set as a synchronised subset of the *Planning Horizon* to provide a correct computation, i.e. a match regarding the operation dates and the number of steps.

Report contains a detailed *Field List* with all of the possible results on an object level. The properties listed in the *Field List* can be selected, e.g. only for the 'Production' category in the *Generators* class, or for the whole *class*, like *Generators*.

Before executing the run, the user must be assured that all of the *memberships* are created, i.e. the objects mentioned above are defined and assigned to the proper model.

As it was stated above, the computation time depends on the provided settings, size of the model and the specified accuracy of the results. The solutions are displayed in a separate tab. They can be visualised in a graphical forms or listed in the tables. Some general parameters can be displayed for each simulation phase and their values can vary since the LT plan gives an approximate overview and ST is the most accurate one.

Appendix C – Modelling assumptions (PLEXOS, OSeMOSYS)

Models' alignment

Table 1 below presents the main differences between the PLEXOS and OSeMOSYS models, as well as applied assumptions. The provided changes are common both for Germany and Poland. The listed properties in OSeMOSYS are aligned to the ones used in PLEXOS.

An additional change in the *'Base Case'* model set-up in OSeMOSYS for Poland is a timeframe for the nuclear investments, from 2015 in the original OSeMBE model (REEEM, 2019), to 2033 (the latest Polish energy policy, (Ministerstwo Energii, 2018)).

GERMANY & POLAND		
PROPERTY	**PLEXOS**	**OSeMOSYS**
Timeframe	2012-2050	2015-2060 Stable values of the parameters in 2051-2060 as in 2050
Demand	Hourly values in [TWh] (Demand profiles)	Annual values in [PJ] (Specified Annual Demand)
Carbon price	Shadow price [EUR/kg]	Emission Penalty [USD/kg]
Emission Limit	No imposed emission limit	Deleted originally implemented Annual Emission Limit
Variable costs	Variable O&M on a power plant level [EUR/MWh] One fuel price for the whole model [EUR/MWh] Transport charge for the fuels [EUR/MWh]	Average variable costs for the technologies [USD/kWh] Aggregated fuel price and transport charge for the imported/exported fuels [USD/kWh]
Fixed costs	Annual fixed O&M charge on a power plant level [EUR/kW]	Average fixed costs for the technologies [USD/kW]
Capacity	Installed capacity for each power plant [MW]	Aggregated capacity for each fuel and implemented as Residual Capacity [GW]
Fuels	No *geothermal* nor *waste* energy as a fuel; *Hard coal* and *lignite* modelled separately; *Waste* modeled together with *biomass.*	Considering the same set of fuels as in PLEXOS; *Coal* is an aggregation of the properties for *hard coal* and *lignite*; No *biofuel* usage, its capacity moved to one category *biomass.*
New investments	Max new capacity calculated by multiplying the number of max build units in year and their max capacities [MW]	Applying the max capacity limits in the Total Annual Max Capacity Investment property [GW]
Units	1 EUR = 1.11 USD 1 PJ = 277.778 GWh	

Table 1: Aligned properties and main differences between the PLEXOS and OSeMOSYS models (own elaboration).

In the 3rd analyzed model set-up, i.e. *'EUTL stack'* in OSeMOSYS, the set-up used for the *'New Emission Factor'* case was upgraded by changing the *Residual Capacity* property. The capacities for the CHP units were increased what was followed in a decrease of the available capacity for the technologies used as the condensing power plants.

Table 2 below contains the values of original emission factors with the corresponding units. In the last two columns the new emission factors applied both in the *'New Emission Factors'* and *'EUTL stack'* model set-ups, are listed. Three main emission factors for gas, hard coal and heavy oil are applied in OSeMOSYS for the main technologies only. The emission factors in PLEXOS can be found as the *Production Rate* property in the *Emission.Fuels* collection. In the case of OSeMOSYS, the *Emission Activity Ratio* property must be defined.

FUEL	OSeMOSYS [kt/PJ]	OSeMOSYS [kg/MWh]	PLEXOS [kg/MWh]	Unified [kg/MWh]	Unified [kt/PJ]
Blast furnace gas	50.29	181.05	205.00	202.00	56.11
Gas	50.29	181.05	205.00	202.00	56.11
Hard Coal	90.54	325.93	342.00	354.00	98.33
Heavy Oil	70.08	252.28	279.00	279.00	77.50
Light Oil	70.08	252.28	267.00	267.00	74.17
Oil shale	70.08	252.28	384.00	384.00	106.67
Peat	90.54	325.93	400.00	382.00	106.11
Lignite	90.54	325.93	400.00	364.00	101.11

Table 2: Emission factors in the original model set-ups in OSeMOSYS and PLEXOS, and the unified emission factors applied to both of the models in the chosen model set-ups.

The *'New Policy'* scenario developed for both Germany and Poland, is a forecast of the course of events in the case when the policy makers' recommendations enter into force on time. These advices are included in the national energy strategies, for Germany it is mainly the *Energy Concept* (BMU, 2010), and for Poland the latest energy policy (Ministerstwo Energii, 2018). These master plans are also shortly summarized in Appendix A. They do not indicate the exact methods of execution but focus on setting the targets and directions. Thus, their interpretation may differ in the modeling concepts.

The *'New Policy'* scenario is created by duplicating the 3rd model set-up, i.e. *'EUTL stack'* and contains some changes listed in Table 3 below.

OSeMOSYS - *'New Policy'* scenario		
Property/Change	**GERMANY**	**POLAND**
Committed project – model is forced to make the changes by setting *both Total Annual Max -* and *Min Capacity Investment*	25 GW of installed wind offshore capacity by 2035	10.5 GW of installed wind offshore capacity by 2035; 10.5 GW of installed capacity using geothermal energy by 2040; 10.5 GW of installed capacity using biomass by 2040;
RE targets – share of RE in the electricity generation	18% by 2020; 30% by 2030; 45% by 2040; 60% by 2050; 80% by 2060[4]	20% by 2020; 27% by 2030; 34% by 2040; 41% by 2050; 48% by 2060[5]
Selected technologies meeting the above RE targets	Biomass (extraction/ steam turbine/combined cycle), geothermal energy(extraction/conventional), solar utility, wind offshore (long-term), wind onshore (near term)	Biomass (extraction/ steam turbine), geothermal energy (extraction/conventional), solar utility, wind offshore, wind onshore (current, near term)

Table 3: Assumptions and changes provided in the 'New Policy' scenario for Germany and Poland.

The selection of the technologies expected to meet the RE targets was justified by their strong exploitation in the BAU scenario.

[4] IEA. 2010. *Energy Concept – Germany*. [Online] Available at: https://www.iea.org/policiesandmeasures/pams/germany/name-34991-en.php. [Accessed 29 May 2019].
[5] Gram w Zielone. 2019. *Ministerstwo Energii określiło cel OZE na rok 2030*. [Online] Available at: https://gramwzielone.pl/trendy/34067/ministerstwo-energii-okreslilo-cel-oze-na-rok-2030-ambitny. [Accessed 29 May 2019].

Appendix D- Reference Statistics

	A	B	C	D	E	G	H	I	L	M	N	O	P	Q
1	ou	Unit	EIC	ETS_Name	PlantName	StartOfOperation	InstCapEl	CHP_cap	Fuel		Eff. LCP	Eff. ETS16	Eff. ETS17	ff. from C
203	DE	HERDECKE_H6	11WD7HERD2G-H6-X	Cuno-Heizkraftwerk Herdecke	GT Herdecke	2007-10-09 00:00:00	424		Fossil Gas		0.543670235	0.504723618	0.51244898	0.5367
204	DE	KW Hamm-Uentrop Block 10	11WD7KWHU1GBL10E	Du Pont Werk Uentrop Kraftwerk	GuD Hamm	2007-06-22 00:00:00	425		Fossil Gas		0.532340175	7.726153846	8.0352	0.2860
205	DE	KW Hamm-Uentrop Block 20	11WD7KWHU1GBL20B	Du Pont Werk Uentrop Kraftwerk	GuD Hamm	2007-06-22 00:00:00	425		Fossil Gas		0.532340175	7.726153846	8.0352	0.2860
209	DE	Kiel	11WD2KIEL000050P	Gemeinschaftskraftwerk Kiel	HKW Kiel Gemeinschaft	1970-01-11 00:00:00	323	295	Fossil Hard coal		0.320247865	0.316506938	0.3209606	0.3569
212	DE	GKM AG Amprion	11W0-0000-0006-5	Grosskraftwerk Mannheim	KW Mannheim	1921-08-11 00:00:00	691	1500	Fossil Hard coal		0.366253885	0.370285714	0.358641509	0.1361
213	DE	GKM AG DBEnergie	11W0-0000-0004-B	Grosskraftwerk Mannheim	KW Mannheim	1921-08-11 00:00:00	244		Fossil Hard coal		0.366253885	0.370285714	0.358641509	0.0480
214	DE	GKM AG TNG	11W0-0000-0005-8	Grosskraftwerk Mannheim	KW Mannheim	1921-08-11 00:00:00	1036		Fossil Hard coal		0.366253885	0.370285714	0.358641509	0.2040
215	DE	Block GT1	11WD7LUDW5GSDG1Q	Heizkraftwerk GuD Süd (C200)	IKW Chemie Ludwigshafen	1998-01-01 00:00:00	178	240	Fossil Gas		0.358824489	0.361294964	0.36064632	
216	DE	Block GT2	11WD7LUDW5GSDG2O	Heizkraftwerk GuD Süd (C200)	IKW Chemie Ludwigshafen	1998-01-01 00:00:00	167	240	Fossil Gas		0.358824489	0.361294964	0.36064632	
217	DE	HAGEN-KABEL-H45	11WD7GARE5G-H45C	Heizkraftwerk Hagen-Kabel	IKW Hagen	1980-01-10 00:00:00	250	108	Fossil Gas	Oil			0.125393258	0.3311
218	DE	HKW Heilbronn Block 7	11WD4HLBR1C7---4	Heizkraftwerk Heilbronn	HKW Heilbronn	1966-01-01 00:00:00	778	300	Fossil Hard coal		0.332529608	0.342486486	0.340780876	0.2770
219	DE	HERNE_3	11WD7HERN2S-3--W	Heizkraftwerk Herne	HKW Herne	1989-02-05 00:00:00	280		Fossil Hard coal		0.297364361	0.316506938	0.327724138	0.1344
220	DE	HERNE_4	11WD7HERN2S--4-X	Heizkraftwerk Herne	HKW Herne	1989-02-05 00:00:00	460	550	Fossil Hard coal		0.297364361	0.316506938	0.327724138	0.2208
221	DE	Block AGuD	11WD7NORF5GAGUDC	Heizkraftwerk Lausward	KW Lausward	1974-06-30 00:00:00	100	75	Fossil Gas		0.55893205	0.55338843	0.554917127	0.0315
222	DE	Block E	11WD7NORF5G-HTER	Heizkraftwerk Lausward	KW Lausward	1974-06-30 00:00:00	300	140	Fossil Gas		0.55893205	0.55338843	0.554917127	0.0947
223	DE	Block F	11WD7NORF5GGUDFA	Heizkraftwerk Lausward	KW Lausward	1974-06-30 00:00:00	595	300	Fossil Gas		0.55893205	0.55338843	0.554917127	0.1880
225	DE	NIEHL-3	11WD7OPLA1G--318	Heizkraftwerk Niehl	GuD Köln Niehl	1993-01-22 00:00:00	453	265	Fossil Gas		0.505453325	0.449395973	0.491149144	0.2587
226	DE	NIEHL-II-DT	11WD7BOLA5GDTN2T	Heizkraftwerk Niehl	GuD Köln Niehl	1993-01-22 00:00:00	147	370	Fossil Gas		0.505453325	0.449395973	0.491149144	0.0839
227	DE	NIEHL-II-GT	11WD7BOLA5GGTN2E	Heizkraftwerk Niehl	GuD Köln Niehl	1993-01-22 00:00:00	266	370	Fossil Gas		0.505453325	0.449395973	0.491149144	0.1519
229	DE	DESBR____CHP____	11WD7UCHT5XROEMT	Heizkraftwerk Römerbrücke	HKW Römerbrücke	1964-12-14 00:00:00	125	230	Fossil Gas		0.620876912	0.216465517	0.252679245	0.3324
230	DE	Sued GuD1 GT2	11WD2S1G2000097U	Heizkraftwerk Süd GuD	HKW München-Süd	1969-11-27 00:00:00	108	255	Fossil Gas		0.340828406	0.338752108	0.375476636	0.055
231	DE	Sued GuD1 GT3	11WD2S1G3000098K	Heizkraftwerk Süd GuD	HKW München-Süd	1969-11-27 00:00:00	108	255	Fossil Gas		0.340828406	0.338752108	0.375476636	0.055
232	DE	Sued GuD2 DT60	11WD2S260000100F	Heizkraftwerk Süd GuD	HKW München-Süd	1969-11-27 00:00:00	128	463	Fossil Gas		0.340828406	0.338752108	0.375476636	0.0651
233	DE	Sued GuD2 GT61	11WD2S2610001015	Heizkraftwerk Süd GuD	HKW München-Süd	1969-11-27 00:00:00	136	463	Fossil Gas		0.340828406	0.338752108	0.375476636	0.0692
234	DE	Sued GuD2 GT62	11WD2S262000102W	Heizkraftwerk Süd GuD	HKW München-Süd	1969-11-27 00:00:00	136	463	Fossil Gas		0.340828406	0.338752108	0.375476636	0.0692
235	DE	HKW Tiefstack GuD	11WD8TIEF5G-GUDI	Heizkraftwerk Tiefstack	HKW Tiefstack	1994-01-31 00:00:00	127	170	Fossil Gas		0.317040779	0.2025	0.206879506	0.1060

Table 1: Aggregated databases (EUTL, ENTSO-E, LCP) for the thermal units exceeding 100 MW in Germany (own elaboration).

ID	Installation name in EUTL	Emissions 2016 [Mt_{CO2}]	Emissions 2017 [Mt_{CO2}]
776	Heizkraftwerk Flingern - ohne Dampfbereich	0.004	0.001
824	G-Kraftwerk NW 1054088 206	0.719	0.706
825	HKW Rostock Marienehe	0.213	0.213
828	X- Kraftwerk NW 1054088 207	0.085	0.087
838	Kraftwerk Ensdorf Block 3	1.079	1.043
839	Kraftwerk Ensdorf Block 1	0.064	0.047
845	Kraftwerk Weiher III	1.355	0.408
849	Peißenberger Kraftwerks GmbH - Kraftwerk Hausham	0.002	0.002
851	Modellkraftwerk Völklingen	0.622	0.367
852	Kraftwerk Bexbach	1.844	0.508
860	Kraftwerk O10 - Kessel 3-5	0.586	0.724
882	HKW Barmen	0.027	0.044
889	Heizkraftwerk Völklingen	0.870	0.679
939	Kraftwerk Mehrum Block 3	1.757	1.930
963	Kraftwerk Zolling - Block 5 und Hilfskesselanlage	1.640	1.503
969	Kraftwerk Wilhelmshaven	2.811	1.322
995	Kraftwerk Huntorf	0.003	0.005
999	Kraftwerk Farge	0.961	1.260
1000	Gaskraftwerk Emden	0	0
1004	GT Audorf	0.006	0.004
1012	Kraftwerk Kirchmöser	0.300	0.243
1088	Du Pont Werk Uentrop Kraftwerk	0.037	0.029
1089	HWO Dessau	0.002	0
1113	Kraftwerk Kirchlengern	0.004	0.006
1203	Kraftwerk Pleinting	0	0
1205	Kraftwerk Scholven	4.242	4.301
1207	Kraftwerk Irsching	0.056	0.051
1212	GT Itzehoe	0.006	0.003
1221	Kraftwerk Georgsmarienhütte	0.003	0.003
1227	GTKW Ahrensfelde	0	0
1228	Block 4 Bremen	2.845	2.323
1230	Block 3 Bremen	0	0
1231	GTKW Thyrow	0.003	0.001
1248	Kraftwerk Hastedt Block 14	0	0
1250	Gasturbinenkraftwerk Brunsbüttel	0.002	0
1264	Kraftwerk Zolling - Gasturbinenanlage	0	0.001
1290	Kraftwerk Knepper	0	0
1291	Kraftwerk Heyden	3.004	1.978
1309	Kraftwerk Rostock	2.637	2.336
1312	Heizkraftwerk Herne	2.174	1.531
1313	Kraftwerk Lünen	1.179	0.995
1318	KW Voerde	4.488	1.046
1333	Kraftwerk Ummeln	0	0
1361	Spitzenstromanlage Großkayna	0.006	0.015
1376	Kraftwerk Schkopau	5.133	5.502
1379	Kraftwerk Staudinger - Block 4	0	0
1380	Grosskraftwerk Mannheim	7.876	6.854

1399	Kraftwerk Bergkamen	2.824	1.640
1419	Kraftwerk Buschhaus	1.798	0
1429	Kraftwerk Staudinger - Block 1	0	0
1446	Kraftwerk Franken I	0.125	0.227
1447	Kraftwerk Ingolstadt	0.042	0.036
1448	Kraftwerk Robert Frank Block 4	0	0.001
1450	Kraftwerk Altbach	1.920	1.250
1452	Heizkraftwerk Heilbronn	2.388	2.395
1453	Kraftwerk Boxberg Werk III	8.877	8.550
1454	Kraftwerk Boxberg Werk IV	9.697	10.583
1455	Kraftwerk Marbach	0.006	0.018
1456	Kraftwerk Jänschwalde	23.756	23.627
1457	RDK Karlsruhe	2.986	3.842
1459	Kraftwerk Schwarze Pumpe	12.199	11.387
1460	Kraftwerk Lippendorf	10.790	11.376
1464	Kraftwerk Walheim	0.057	0.075
1474	Kraftwerk Westfalen	0.255	0
1477	Kraftwerk Werne	2.903	1.708
1479	Kraftwerk Emsland (Lingen)	1.692	1.694
1480	Kraftwerk Ibbenbüren	3.864	2.513
1481	Kraftwerk Gersteinwerk	0.001	0.025
1485	Kraftwerk Dormagen	1.586	1.389
1486	Kraftwerk Huckingen	2.898	3.222
1526	Kraftwerk Werdohl-Elverlingsen	0.379	0.189
1588	HKW Dessau	0.150	0.174
1592	KW West Voerde	0.915	0.262
1601	Kraftwerk Goldenberg	0.899	0.848
1605	Kraftwerk Frimmersdorf	4.359	3.582
1606	Kraftwerk Neurath	31.324	29.900
1607	Kraftwerk Weisweiler	18.747	18.945
1649	Kraftwerk Niederaußem	24.835	27.174
1710	Kraftwerk Veltheim	0	0
1759	Kraftwerk Mehrum Hilfskessel	0.004	0.006
1784	Kraftwerk Robert Frank - Hilfskesselanlage	0	0
1785	Kraftwerk Staudinger - Block 3	0	0
1876	Kraftwerk Staudinger	2.427	1.889
1888	Gas und Dampfturbinen Kraftanlage Knapsack	0.376	0.327
4148	Kraftwerk Irsching Block 4	0.030	0.007
	TOTAL:	**223.75**	**206.93**

Table 2: List of the condensing power plants in Germany registered in the EUTL database (own elaboration based on (EUTL, 2017)).

ID	Installation name in EUTL	Emissions 2016 [Mt_{CO2}]	Emissions 2017 [Mt_{CO2}]
1	PGE GiEK S.A. Oddział Elektrownia Bełchatów	34.94	37.65
2	PGE GiEK S.A. Oddział Elektrownia Opole	5.92	6.28
3	PGE GiEK S.A. Oddział Elektrownia Turów	7.84	7.11
4	ELEKTROWNIA KOZIENICE	12.01	11.19
5	Instalacja do spalania paliw (POLANIEC)	7.73	7.03
6	PGE Energia Ciepła S.A. Oddział w Rybniku	7.05	6.48
8	TAURON Wytwarzanie SA O. Elektrownia Stalowa Wola	0.52	0.45
9	TAURON Wytwarzanie SA O. Elektrownia Jaworzno III	4.51	6.01
11	TAURON Wytw. SA Elektr. Jaworzno III Elektr. II	0.97	0.91
12	TAURON Wytwarzanie SA O. Elektrownia Łaziska	3.70	3.88
14	TAURON Wytwarzanie SA O. Elek. Łagisza w Będzinie	2.06	1.87
15	TAURON Wytw. SA O. Elektrownia Siersza w Trzebini	1.60	1.54
16	PGE GiEK S.A. Oddział Zespół Elektrowni Dolna Odra	4.34	3.85
20	ELEKTROWNIA OSTROŁĘKA B	2.30	2.32
21	ELEKTROWNIA PĄTNÓW	5.37	4.77
22	ELEKTROWNIA KONIN	0.63	0.64
23	ELEKTROWNIA ADAMÓW	3.44	2.85
24	CEZ Chorzów S.A.	1.18	1.35
931	ELEKTROWNIA PĄTNÓW II	2.03	2.61
208182	Elektrownia gazowo-parowa CCGT	0	0
209933	Elektrownia Kozienice - blok energetyczny 11	0	0
209934	Elektrownia Kozienice - kotłownia rozruchowa	0	0
209964	Elektrownia - Blok Gazowo - Parowy Płock	0	0
	TOTAL	**108.13**	**108.79**

Table 3: List of the condensing power plants in Poland registered in the EUTL database (own elaboration based on (EUTL, 2017)).

Emission factors [t_{CO2}/MWh]	
Lignite	0.364
Anthracite	0.354
Other bituminous coal	0.341
Sub-bituminous coal	0.346
Natural gas	0.202
Municipal waste	0.330
Biogas	0.197
Peat	0.382
Motor gasoline	0.249
Gas/diesel oil	0.267
Coking coal	0.335
Brown coal briquettes	0.355
Coke oven coke	0.343
Coke oven gas	0.403
Blast furnace gas	0.891
Refinery gas	0.240
Liquefied petroleum gas	0.227
Petroleum coke	0.342

Table 4: Emission factors for the EU Member States (Koffi, 2017).

5 a)

DE: Transformation Input: Electricity & Heat generation [Mt_{CO2}]		
	2016	**2017**
Anthracite	1.51	1.59
Coking coal	7.39	9.45
Other bituminous coal	91.01	69.78
Lignite	140.94	138.93
Coke oven coke	0.003	0.003
Brown coal briquettes	1.88	1.65
Coke oven gas	2.57	2.84
Blast furnace gas	18.10	17.76
Other recovered gases	0.40	0.43
Refinery gas	0.44	0.38
Liquefied petroleum gas	0.21	0.22
Gas oil/diesel oil	0.99	0.90
Fuel oil	0.75	0.78
Petroleum coke	0.09	0.08
Other oil products	1.63	1.63
Natural gas	40.89	43.02
TOTAL:	308.82	289.45

5 b)

DE: Gross Electricity production [Mt_{CO2}]		
	2016	**2017**
Anthracite	0.58	0.62
Coking coal	2.85	3.68
Other bituminous coal	34.79	27.56
Lignite	53.83	53.48
Brown coal briquettes	0.58	0.51
Coke oven gas	1.08	1.21
Blast furnace gas	7.12	6.31
Other recovered gases	0.16	0.16
Refinery gas	0.19	0.15
Liquefied petroleum gas	0.07	0.07
Gas oil/diesel oil	0.25	0.24
Fuel oil	0.32	0.29
Petroleum coke	0.05	0.06
Other oil products	0.65	0.64
Natural gas	16.62	17.71
TOTAL:	119.16	112.71

5 c)

DE: Gross Electricity production - Main activity producer CHP [Mt_{CO2}]		
	2016	**2017**
Anthracite	0.06	0.10
Coking coal	0.30	0.60
Other bituminous coal	3.50	4.17
Lignite	1.41	1.34
Brown coal briquettes	0.16	0.11
Other recovered gases	0.0002	0.0002
Gas oil/diesel oil	0.08	0.07
Fuel oil	0.01	0.01
Petroleum coke	0.00	0.001026
Other oil products	0.00	0.001068
Natural gas	7.80	8.21
TOTAL:	13.32	14.60

5 d)

DE: Gross Heat production - Main activity producer CHP [Mt_{CO2}]		
	2016	**2017**
Anthracite	0.14	0.17
Coking coal	0.69	1.03
Other bituminous coal	8.06	7.17
Lignite	3.29	2.99
Brown coal briquettes	0.37	0.27
Other recovered gases	0.002	0.002
Gas oil/diesel oil	0.04	0.03
Fuel oil	0.03	0.03
Petroleum coke	0.003	0.002
Other oil products	0.004	0.003
Natural gas	7.69	8.11
TOTAL:	20.32	19.80

5 e)

DE: Gross Heat production [Mt_{CO2}]		
	2016	**2017**
Anthracite	0.15	0.19
Coking coal	0.75	1.11
Other bituminous coal	8.75	7.89
Lignite	3.34	3.01
Coke oven coke	0.0003	0.0005
Brown coal briquettes	0.50	0.39
Coke oven gas	0.07	0.06
Other recovered gases	0.002	0.002
Liquefied petroleum gas	0.00	0.00
Gas oil/diesel oil	0.27	0.23
Fuel oil	0.05	0.04
Petroleum coke	0.003	0.002
Other oil products	0.06	0.06
Natural gas	11.87	12.31
TOTAL:	25.82	25.30

Table 5: Estimated levels of generated CO_2 emissions [Mt] in Germany, based on the fuel consumption available in the energy balances prepared by Eurostat (own elaboration based on (Eurostat, 2019)), calculated for the following categories:

a) *Transformation Input – Electricity and Heat generation;*
b) *Gross electricity production;*
c) *Gross electricity production – Main activity producer CHP;*
d) *Gross heat production – Main activity producer CHP;*
e) *Gross Heat production.*

6 a)

PL: Transformation Input: Electricity & Heat generation [Mt_{CO2}]		
	2016	**2017**
Coking coal	0.21	0.26
Other bituminous coal	90.15	89.74
Lignite	49.03	50.24
Coke oven gas	2.55	2.36
Blast furnace gas	3.62	3.93
Other recovered gases	0.20	0.10
Refinery gas	0.08	0.04
Gas oil/diesel oil	0.09	0.14
Fuel oil	1.23	1.12
Natural gas	3.96	4.68
TOTAL:	151.13	152.61

6 b)

PL: Gross Electricity production [Mt_{CO2}]		
	2016	**2017**
Coking coal	0.04	0.06
Other bituminous coal	27.04	26.88
Lignite	18.53	18.99
Coke oven gases	0.79	0.61
Blast furnace gas	0.47	0.63
Other recovered gas	0.09	0.01
Refinery Gas	0.04	0.02
Gas oil/diesel oil	0.02	0.03
Fuel oil	0.56	0.49
Natural gas	1.58	2.03
TOTAL:	49.15	49.74

6 c)

PL: Gross Electricity production - Main activity producer CHP [Mt_{CO2}]		
	2016	**2017**
Other bituminous coal	26.11	25.99
Lignite	17.77	18.03
Coke oven gases	0.32	0.21
Blast furnace gas	0.47	0.63
Other recovered gas	0.02	0.01
Gas oil/diesel oil	0.01	0.02
Fuel oil	0.12	0.11
Natural gas	1.14	1.26
TOTAL:	45.96	46.28

6 d)

PL: Gross Heat production - Main activity producer CHP [Mt_{CO2}]		
	2016	**2017**
Other bituminous coal	12.96	12.98
Lignite	0.58	0.60
Coke oven gases	0.24	0.59
Blast furnace gas	1.67	1.81
Other recovered gas	0.08	0.04
Gas oil/diesel oil	0.01	0.02
Fuel oil	0.02	0.02
Natural gas	0.69	0.84
TOTAL:	16.26	16.89

6 e)

PL: Gross Heat production [Mt_{CO2}]		
	2016	**2017**
Coking coal	0.10	0.12
Other bituminous coal	22.17	22.11
Lignite	0.61	0.64
Coke oven gas	0.30	0.64
Blast furnace gas	1.67	1.81
Other recovered gas	0.09	0.05
Oil	0.27	0.31
Refinery gas	0.01	0.01
Gas oil/diesel oil	0.05	0.06
Fuel oil	0.21	0.23
Natural gas	1.18	1.38
TOTAL:	26.66	27.35

Table 6: Estimated levels of generated CO_2 emissions [Mt] in Poland, based on the fuel consumption available in the energy balances prepared by Eurostat (own elaboration based on (Eurostat, 2019)), calculated for the following categories:

- *a) Transformation Input – Electricity and Heat generation;*
- *b) Gross electricity production;*
- *c) Gross electricity production – Main activity producer CHP;*
- *d) Gross heat production – Main activity producer CHP;*
- *e) Gross Heat production.*

Appendix E - Graphs

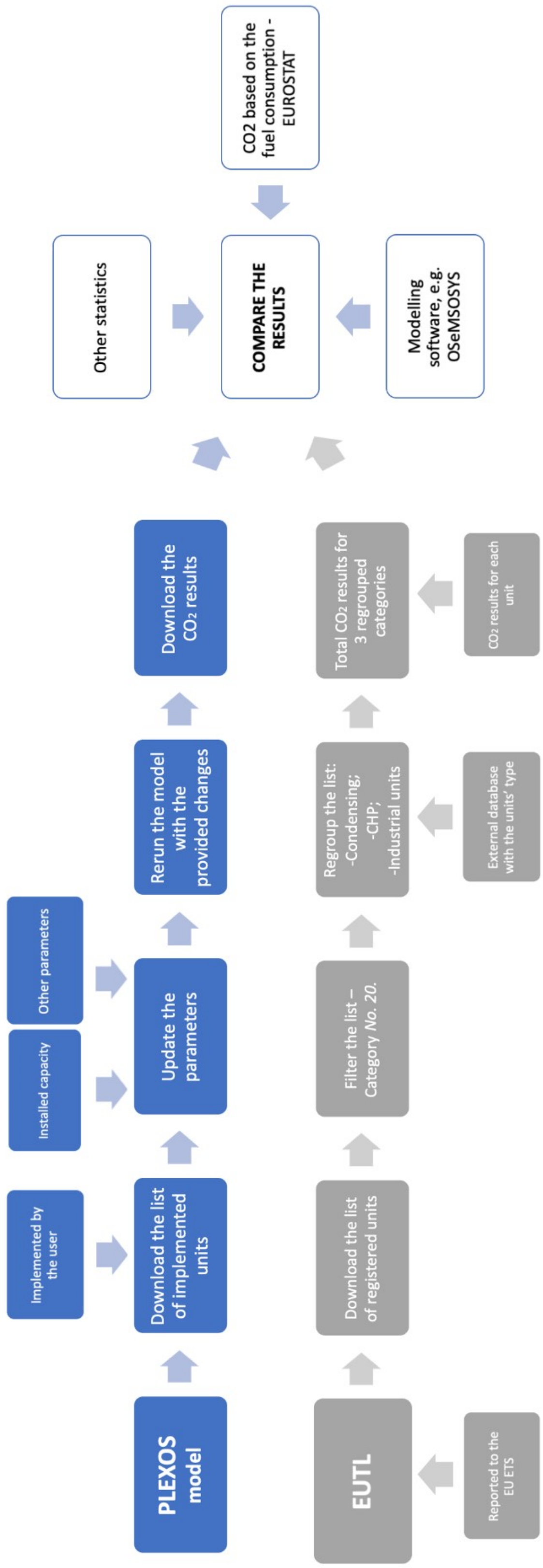


Figure 1: Schedule of a PLEXOS power system model validation in terms of CO_2.

Appendix F – Results

Tables 1 and 2 below present the results of historical CO_2 emissions in 2016 and 2017 across three PLEXOS and three OSeMOSYS model set-ups in Germany and Poland, accordingly. The results are compared with the emissions calculated based on the national fuel consumption documented in the Eurostat energy balances. The latter enables the electricity-related emissions calculation derived from both the condensing power plants and CHP units. The calculated emissions from Eurostat are a reference base; thus, the percentage deviations of the remaining model set-ups are also listed in Tables 1 and 2 below.

GERMANY – Electricity-related CO_2 emissions from the condensing power plants and CHP units				
	2016		**2017**	
Eurostat	283.00	100.0%	264.15	100.0%
PLEXOS 1	296.84	104.9%	271.8	102.9%
PLEXOS 2	300.54	106.2%	274.43	103.9%
PLEXOS 3	293.28	103.6%	268.59	101.7%
OSeMOSYS 1	240.60	85.0%	238.59	90.3%
OSeMOSYS 2	264.20	93.4%	261.94	99.2%
OSeMOSYS 3	262.61	92.8%	260.43	98.6%

Table 1: Electricity-related CO_2 emissions from the condensing power plants and CHP units in Germany in 2016 and 2017.

POLAND – Electricity-related CO_2 emissions from the condensing power plants and CHP units				
	2016		**2017**	
Eurostat	124.47	100.0%	125.26	100.0%
PLEXOS 1	119.09	95.7%	126.18	100.7%
PLEXOS 2	119.47	96.0%	126.77	101.2%
PLEXOS 3	118.59	95.3%	124.45	99.4%
OSeMOSYS 1	89.11	71.6%	85.70	68.4%
OSeMOSYS 2	96.95	77.9%	93.32	74.5%
OSeMOSYS 3	96.98	77.9%	91.67	73.2%

Table 2: Electricity-related CO_2 emissions from the condensing power plants and CHP units in Poland in 2016 and 2017

Table 3 below presents the historical results of electricity-related CO_2 emissions derived only from the condensing power plants across three PLEXOS model set-ups in Germany in 2016 and 2017. The model outcome is compared with the emissions documented in the EUTL. The latter is chosen as a reference case and the corresponding percentage change of the PLEXOS model set-ups is calculated to indicate a magnitude of differences.

GERMANY – Electricity-related CO_2 emissions from the condensing power plants only				
	2016		**2017**	
EUTL	238.90	100%	221.17	100%
PLEXOS 1	267.27	112%	245.10	111%
PLEXOS 2	270.66	113%	247.37	112%
PLEXOS 3	259.86	109%	238.30	108%

Table 3: Electricity-related CO_2 emissions from the condensing power plants (only) in Germany in 2016 and 2017.

The results gathered in the Table 3 above are presented graphically in Figure 1 below.

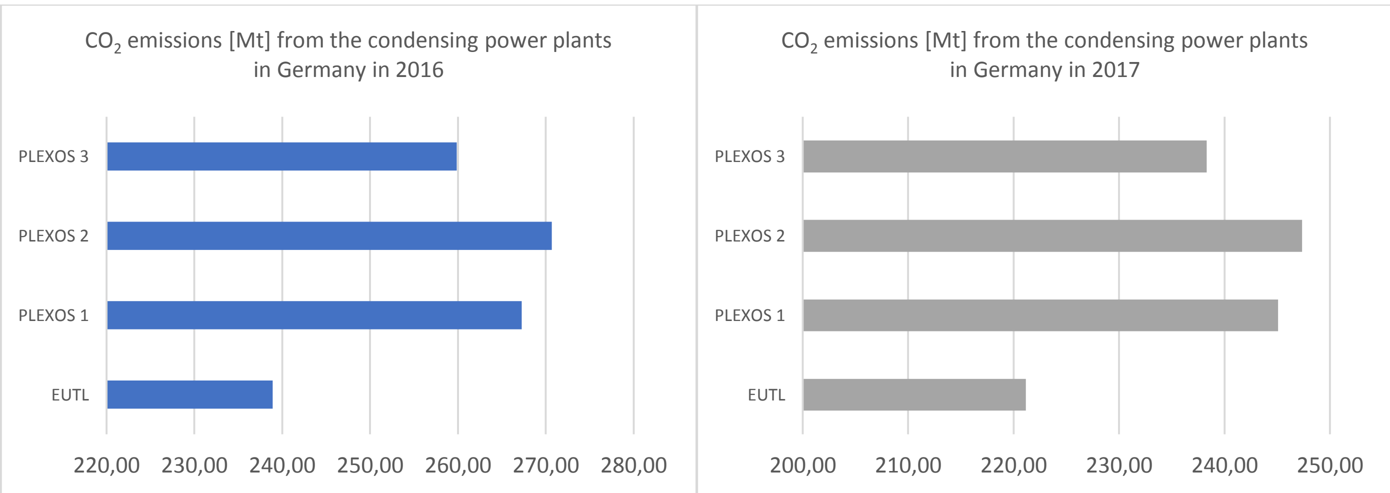


Figure 1: Comparison of the CO_2 emissions [Mt] derived from the condensing power plants across three PLEXOS model set-ups and the EUTL as a reference case in Germany in a) 2016, b) 2017.

Table 4 is a counterpart of the Table 3 above, but for Poland.

By analogy, Figure 2 is a graphical presentation of the Table 4 illustrating the level of differences of the historical CO_2 emissions derived from the condensing power plants (only) in Poland across three PLEXOS model set-ups and the EUTL as a reference case.

POLAND – Electricity-related CO_2 emissions from the condensing power plants only				
	2016		**2017**	
EUTL	108.71	100%	109.14	100%
PLEXOS 1	111.06	102%	117.85	108%
PLEXOS 2	111.19	102%	118.20	108%
PLEXOS 3	110.04	101%	114.71	105%

Table 4: Electricity-related CO_2 emissions from the condensing power plants (only) in Poland in 2016 and 2017.

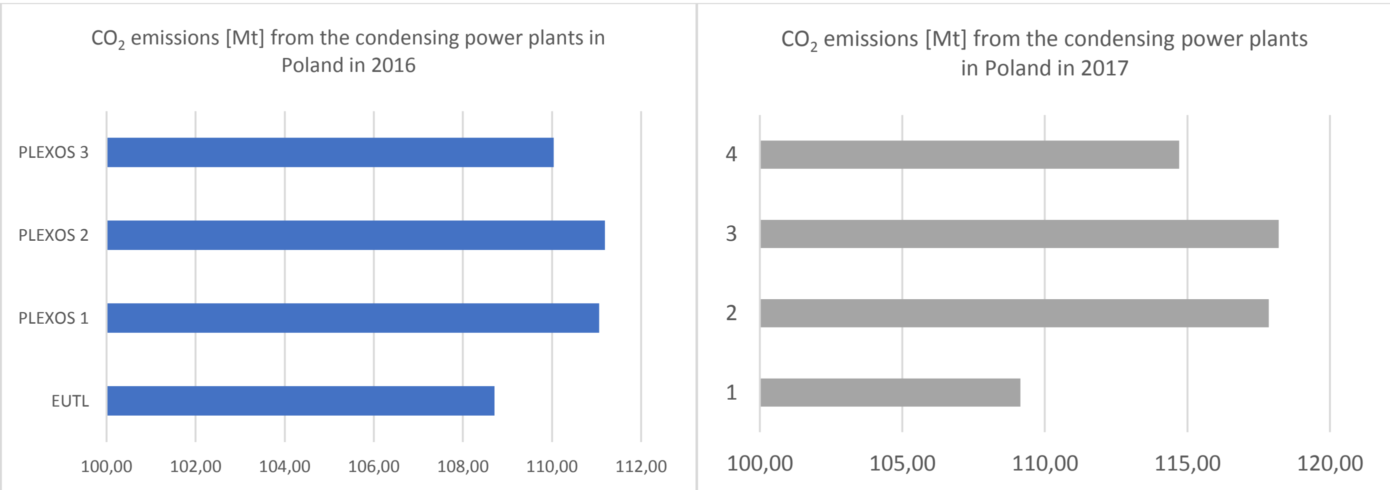


Figure 2: Comparison of the CO_2 emissions [Mt] derived from the condensing power plants across three PLEXOS model set-ups and the EUTL as a reference case in Poland in a) 2016, b) 2017.

Figure 3 and 4 present the trends of predicted CO_2 emissions in Germany between 2019-2025 across analyzed model set-ups in PLEXOS and OSeMOSYS models accordingly.

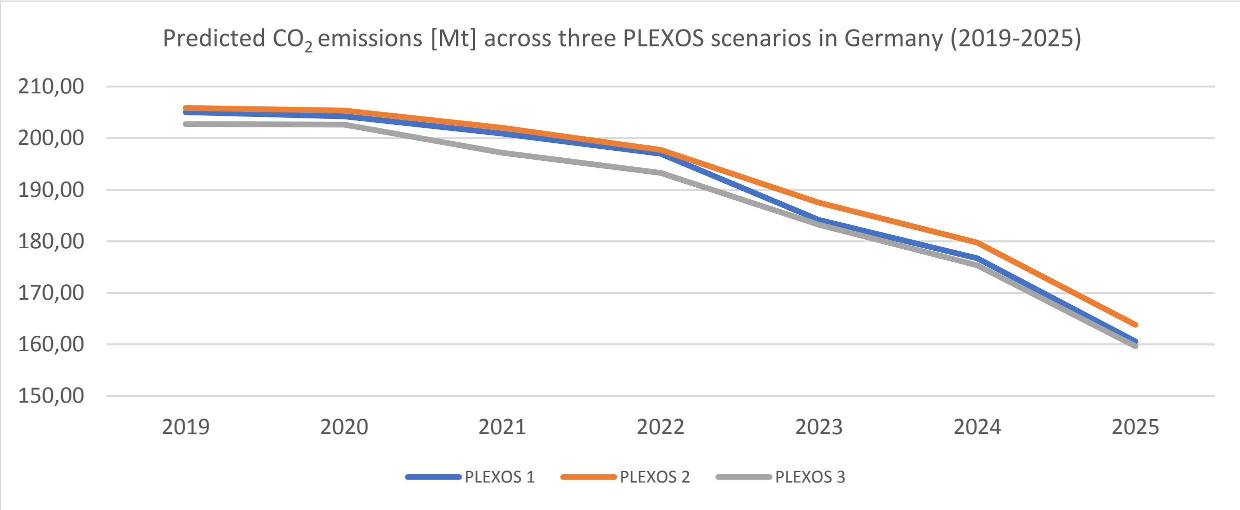


Figure 3: Predicted CO_2 emissions [Mt] across three PLEXOS model set-ups in Germany (2019-2025).

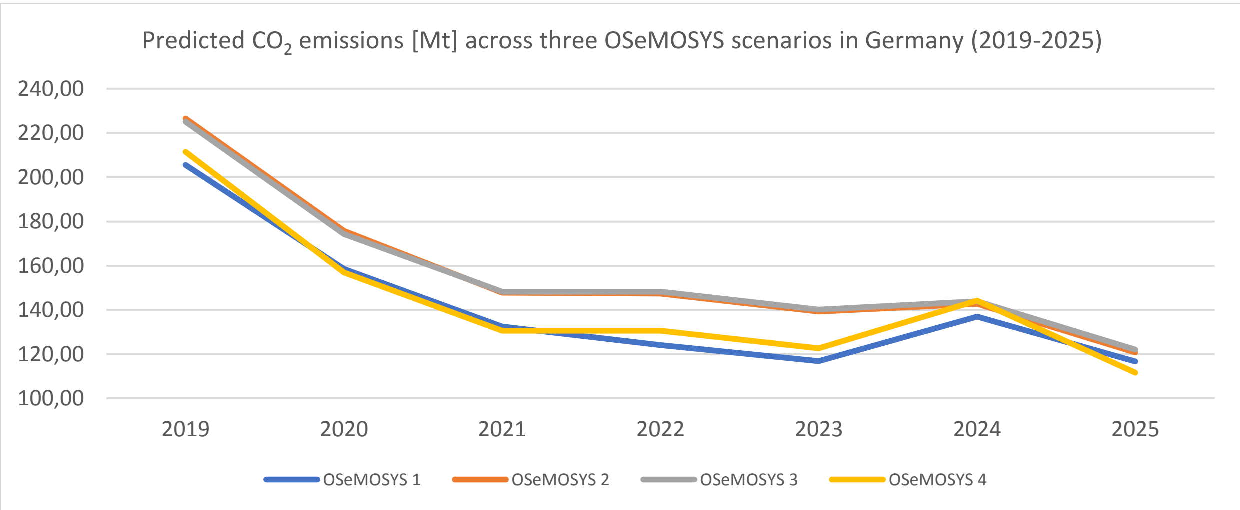


Figure 4: Predicted CO_2 emissions [Mt] across four OSeMOSYS model set-ups in Germany (2019-2025).

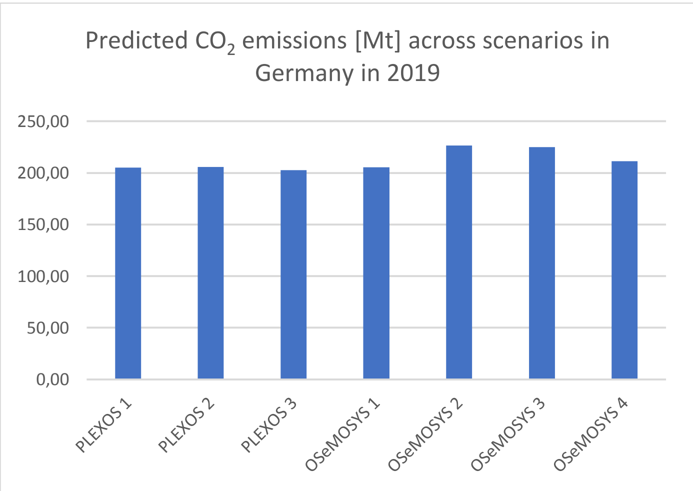
The 1st model set-up of the PLEXOS model built for Germany, i.e. *'Base Case'*, was chosen as a referential point of comparison and the percentage changes calculation across the remaining PLEXOS and OSeMOSYS model set-ups, was done. A magnitude of differences between them for each year (2019-2025) is collected in Table 5 below.

GERMANY - National level percentages changes of emissions (2019-2025)							
	2019	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
PLEXOS 1	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
PLEXOS 2	100.4%	100.5%	100.5%	100.4%	101.8%	101.7%	102.0%
PLEXOS 3	98.9%	99.2%	98.1%	98.1%	99.5%	99.3%	99.4%
OSeMOSYS 1	100.3%	77.6%	66.0%	63.0%	63.5%	77.5%	72.7%
OSeMOSYS 2	110.5%	86.0%	73.6%	74.8%	75.6%	80.8%	75.2%
OSeMOSYS 3	109.8%	85.3%	73.8%	75.3%	76.1%	81.5%	76.0%
OSeMOSYS 4	103.1%	76.8%	65.0%	66.3%	66.6%	81.6%	69.6%

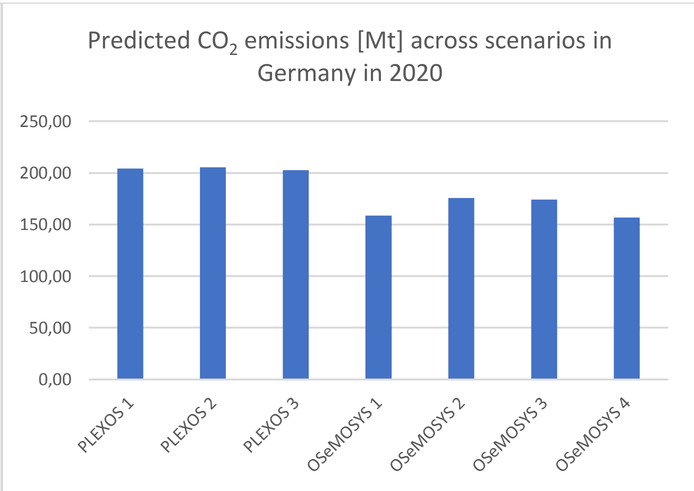
Table 5: National level percentages changes of predicted CO_2 emissions across three PLEXOS and four OSeMOSYS model set-ups in Germany (2019-2025).

The results of predicted CO_2 emissions across model set-ups in Germany are compiled for each analyzed year in a corresponding part of Figure 5 below.

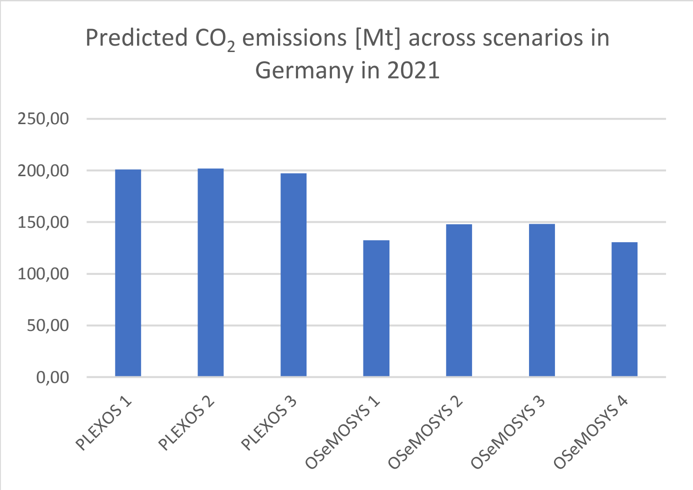
a)



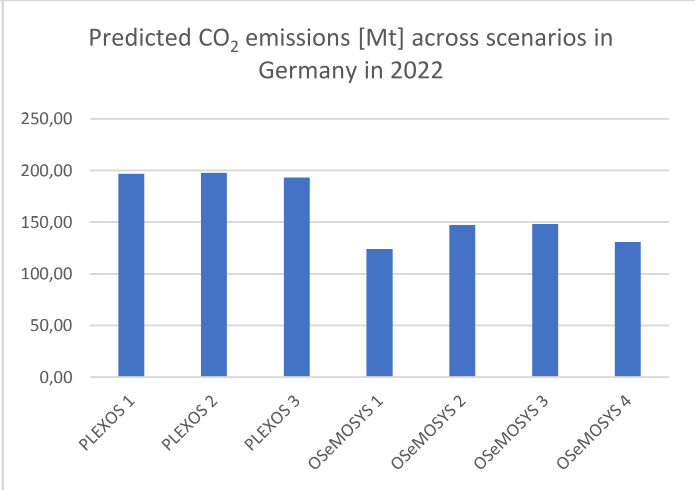
b)



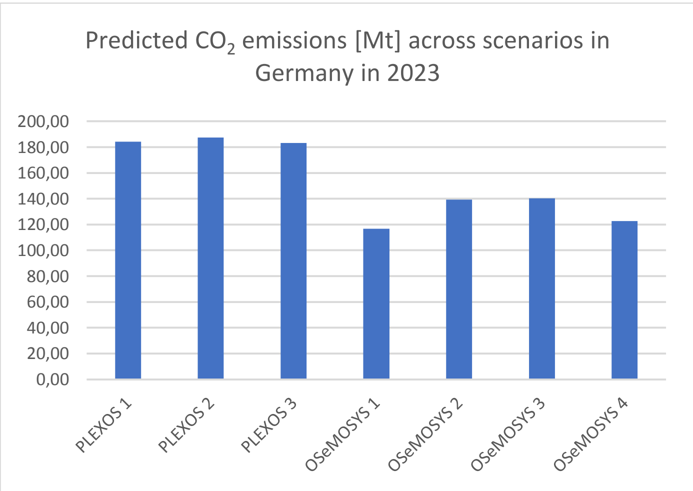
c)



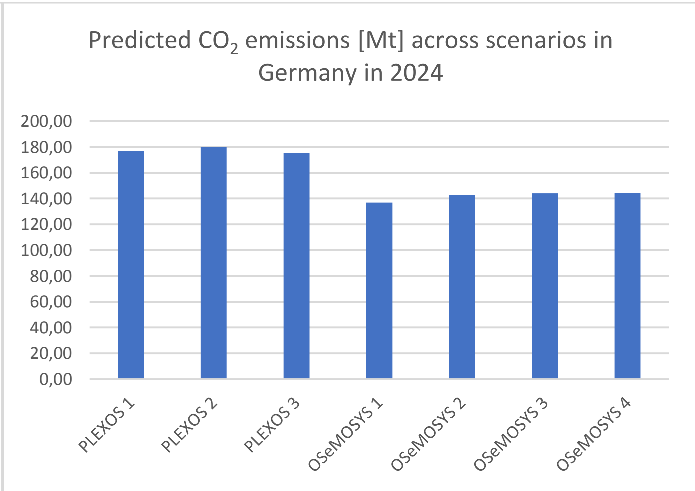
d)



e)



f)



g)

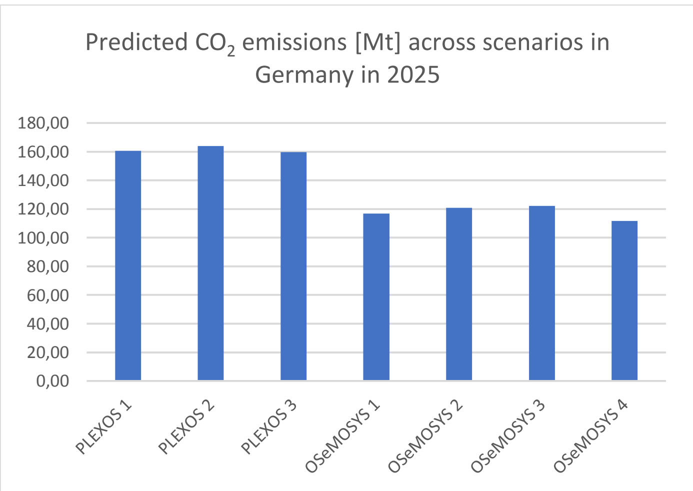


Figure 5: Predicted CO_2 emissions [Mt] across model set-ups in Germany in a) 2019, b) 2020, c) 2021, d) 2022, e) 2023, f) 2024, g) 2025.

Figure 6 and 7 present the trends of predicted CO_2 emissions in Poland between 2019-2025 across analyzed model set-ups in PLEXOS and OSeMOSYS models accordingly.

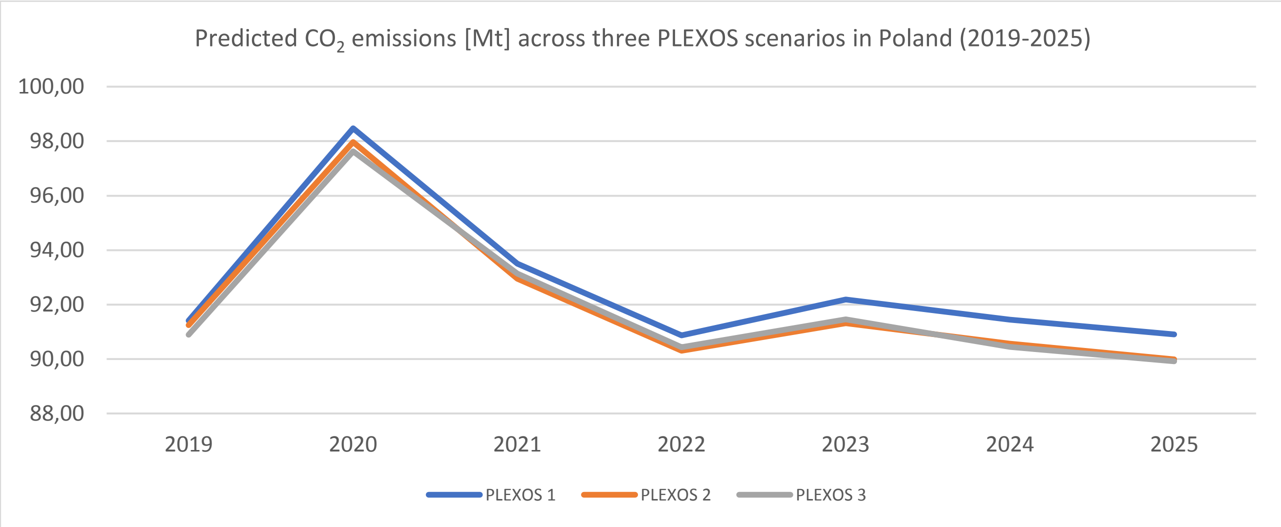


Figure 6: Predicted CO_2 emissions [Mt] across three PLEXOS model set-ups in Poland (2019-2025).

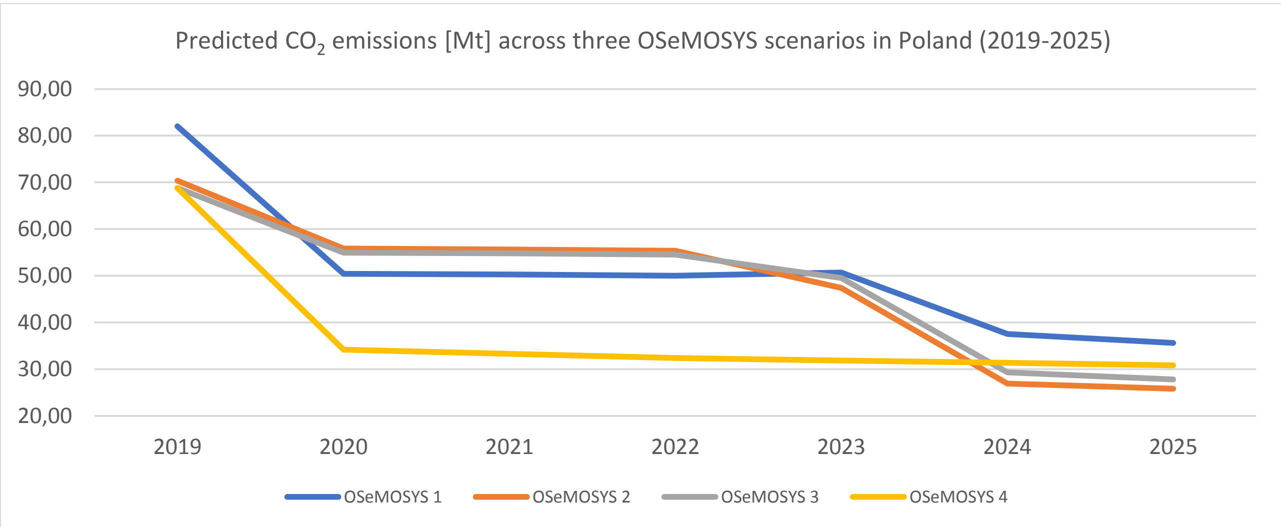


Figure 7: Predicted CO_2 emissions [Mt] across four OSeMOSYS model set-ups in Poland (2019-2025).

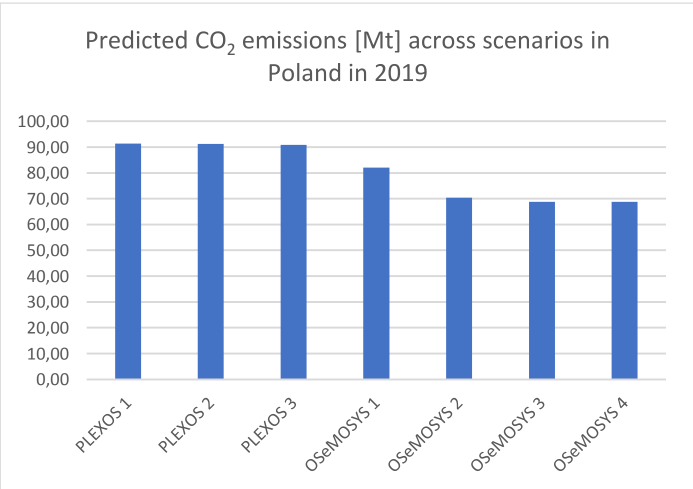
By analogy to the German case above, the 1st model set-up of the PLEXOS model built for Poland, i.e. *'Base Case'*, was chosen as a referential point for the comparison and the percentage changes calculation across the remaining PLEXOS and OSeMOSYS model set-ups. A magnitude of differences between them for each year (2019-2025) is collected in Table 6 below.

POLAND - National level percentages changes of emissions (2019-2025)							
	2019	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
PLEXOS 1	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
PLEXOS 2	99.8%	99.5%	99.4%	99.4%	99.1%	99.0%	99.0%
PLEXOS 3	99.4%	99.1%	99.6%	99.5%	99.2%	98.9%	98.9%
OSeMOSYS 1	89.7%	51.2%	53.7%	55.0%	54.9%	41.0%	39.2%
OSeMOSYS 2	77.0%	56.7%	59.5%	60.9%	51.4%	29.4%	28.4%
OSeMOSYS 3	75.3%	55.8%	58.6%	60.0%	53.7%	32.1%	30.5%
OSeMOSYS 4	75.3%	34.7%	35.6%	35.6%	34.5%	34.3%	33.9%

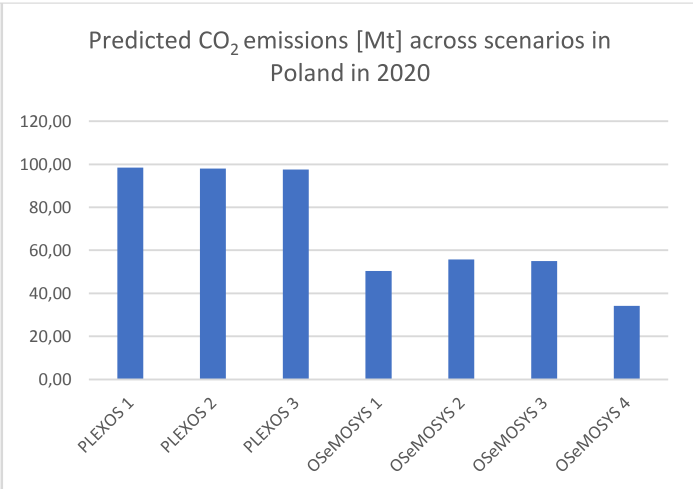
Table 6: National level percentages changes of predicted CO_2 emissions across three PLEXOS and four OSeMOSYS model set-ups in Poland (2019-2025).

The results of predicted CO_2 emissions across model set-ups in Poland are compiled for each analyzed year in a corresponding part of Figure 8 below.

a)



b)



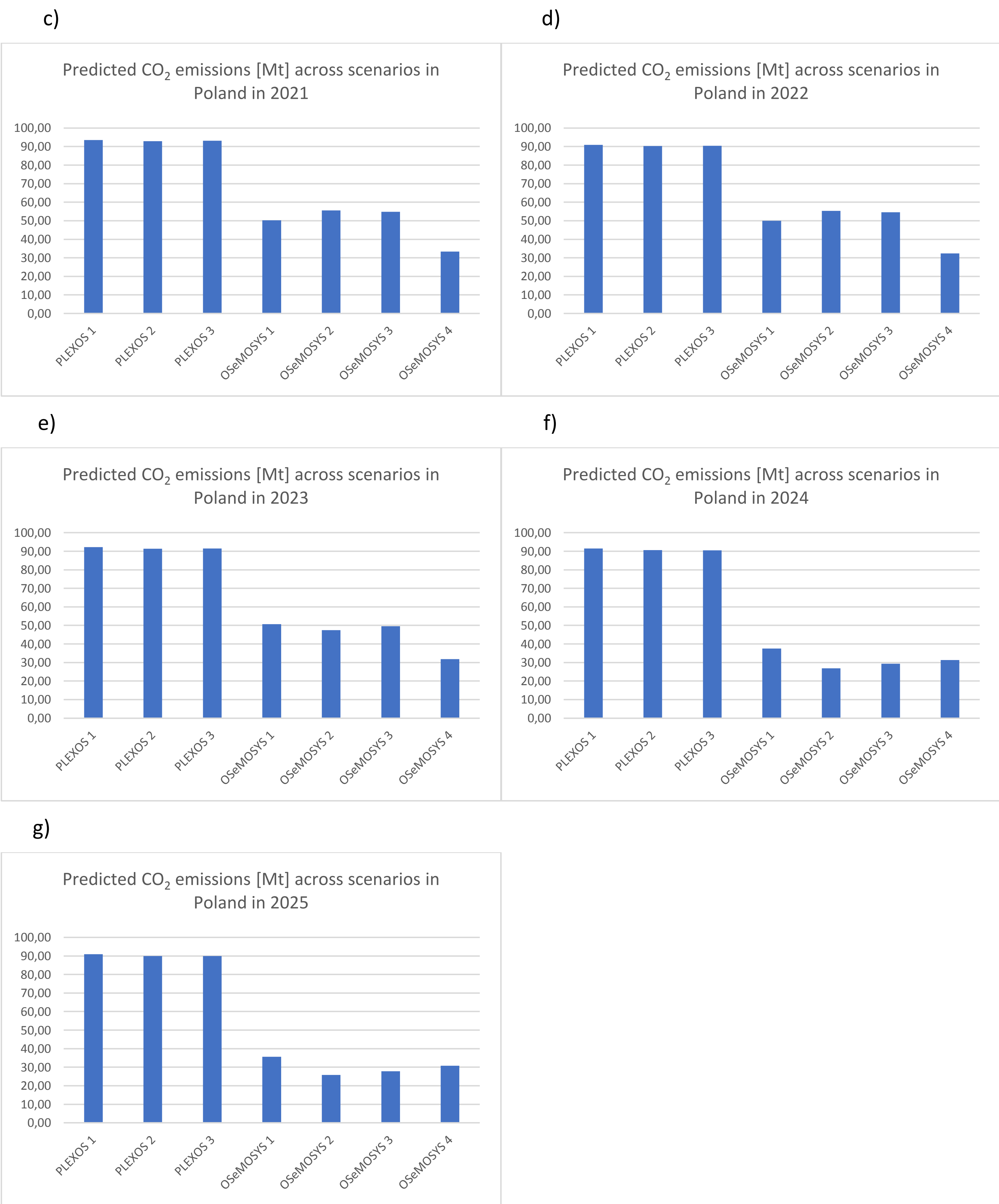


Figure 8: Predicted CO_2 emissions [Mt] across model set-ups in Poland in a) 2019, b) 2020, c) 2021, d) 2022, e) 2023, f) 2024, g) 2025.

Table 7 below gathers the data used for an analysis of the top ten most emitting power plants in Germany and top seven ones in Poland.

	ID	Power plant	Fuel	EU ETS 2016				EU ETS 2017			
				Installed capacity 2016 [MW]	CO_2 [Mt] EUTL 2016	POWER [TWh] EUTL 2016	CO_2 intensity 2016 [t/MWh]	Installed capacity 2017 [MW]	CO_2 [Mt] EUTL 2017	POWER [TWh] EUTL 2017	CO_2 intensity 2017 [t/MWh]
PL	1	**Bełchatów**	LI	5030	34.94	30.27	1.10	5102	37.64	32.90	1.10
PL	4	**Kozienice**	HC	2919	12.01	12.84	0.90	2941	11.19	12.00	0.90
PL	3	**Turów**	LI	1488	7.84	7.30	1.11	1488	7.11	6.70	1.10
PL	5	**Połaniec**	HC	1657	7.73	10.21	0.78	1882	7.03	9.20	0.80
PL	6	**Rybnik**	HC	1555	7.05	7.41	0.99	1790	6.48	6.80	1.00
PL	2	**Opole**	HC	1532	5.92	6.47	0.96	1532	6.28	6.60	1.00
PL	9	**Jaworzno III**	HC	1345	4.51	3.94	0.99	1345	6.01	5.80	1.00
DE	1606	**Neurath**	LI	4168	31.32	28.46	1.10	4212	29.90	27.10	1.20
DE	1649	**Niederaußem**	LI	3430	24.83	21.00	1.22	3398	27.17	23.60	1.20
DE	1456	**Jänschwalde**	LI	2790	23.76	19.99	1.19	2998	23.63	19.60	1.20
DE	1607	**Weisweiler**	LI	1800	18.75	15.05	1.20	2363	18.95	15.20	1.20
DE	1459	**Schwarze Pumpe**	LI	1500	12.20	10.81	1.09	1510	11.39	10.10	1.10
DE	1460	**Lippendorf**	LI	1750	10.78	11.42	0.99	1782	11.38	11.90	1.00
DE	1454	**Boxberg Werk IV**	LI	1497	9.70	9.28	1.00	1470	10.58	10.20	1.00
DE	1453	**Boxberg Werk III**	LI	930	8.87	7.56	1.19	1000	8.55	7.20	1.20
DE	1380	**Mannheim**	HC	1115	7.87	8.35	0.96	1971	6.86	7.20	1.00
DE	206180	**Moorburg**	HC	1600	5.55	6.85	0.80	1600	6.16	7.70	0.80
				PLEXOS New Emission Factor 2016				**PLEXOS New Emission Factor 2017**			
	ID	Power plant	Fuel	Installed capacity 2016 [MW]	CO_2 [Mt] NEF 2016	Installed capacity 2016 [MW]	CO_2 [Mt] NEF 2016	Installed capacity 2016 [MW]	CO_2 [Mt] NEF 2016	Installed capacity 2016 [MW]	CO_2 [Mt] NEF 2016
PL	1	**Bełchatów**	LI	5442	40.08	5442	40.08	5442	40.08	5442	40.08
PL	4	**Kozienice**	HC	2840	12.16	2840	12.16	2840	12.16	2840	12.16
PL	3	**Turów**	LI	965	4.66	965	4.66	965	4.66	965	4.66
PL	5	**Połaniec**	HC	1800	8.54	1800	8.54	1800	8.54	1800	8.54
PL	6	**Rybnik**	HC	1720	5.14	1720	5.14	1720	5.14	1720	5.14
PL	2	**Opole**	HC	1532	7.95	1532	7.95	1532	7.95	1532	7.95
PL	9	**Jaworzno III**	HC	1350	5.41	1350	5.41	1350	5.41	1350	5.41
DE	1606	**Neurath**	LI	4211	35.21	4211	35.21	4211	35.21	4211	35.21
DE	1649	**Niederaußem**	LI	3111	24.76	3111	24.76	3111	24.76	3111	24.76
DE	1456	**Jänschwalde**	LI	2790	24.26	2790	24.26	2790	24.26	2790	24.26
DE	1607	**Weisweiler**	LI	1504	11.93	1504	11.93	1504	11.93	1504	11.93
DE	1459	**Schwarze Pumpe**	LI	1500	10.23	1500	10.23	1500	10.23	1500	10.23
DE	1460	**Lippendorf**	LI	1750	13.27	1750	13.27	1750	13.27	1750	13.27
DE	1454	**Boxberg Werk IV**	LI	1497	10.02	1497	10.02	1497	10.02	1497	10.02
DE	1453	**Boxberg Werk III**	LI	930	7.60	930	7.60	930	7.60	930	7.60
DE	1380	**Mannheim**	HC	15333	8.76	15333	8.76	15333	8.76	15333	8.76
DE	206180	**Moorburg**	HC	1800	8.44	1800	8.44	1800	8.44	1800	8.44

Table 7: Chosen data of the top ten emitting combustion plants in Germany and top seven in Poland (own elaboration based on (EEA. 2018b) and (EUTL, 2017)).